Life Cycle Analysis: Integrated Gasification Combined Cycle (IGCC) Power Plant

Appendix: Process Modeling Data Assumptions and GaBi Modeling Inputs

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A.1 Life Cycle Stage Process Modeling Data Assumptions and GaBi Modeling Inputs

Appendix A details the process modeling data assumptions and GaBi modeling inputs for each of the life cycle (LC) stages considered in this study. For more details on the system boundary and other aspects of this study, please see the main final report. GaBi output data will be shown for air emissions. Results associated with land and all economic modeling assumptions are results are included in the main text.

All stages will be the same for both cases except for Stage #3, which has different assumptions and therefore will be described separately for each case. For each stage, the construction assumptions will be discussed separately from the operations as they often come from different reference sources. When applicable, the commissioning, installation, and decommissioning will also be discussed. For clarity, the following are general descriptions of each term as they are used in this study:

- **Construction**: materials used in the construction of a process (steel used to build a power plant)
- **Commissioning/Installation**: energy used and emissions created to prepare the land and install the processing facility. This is also when land use change occurs. Commissioning and installation are used interchangeably because commissioning is the word typically used in the literature while installation is used in GaBi.
- **Decommissioning**: energy use and emissions associated with removing the processing facility (and returning the land to grassland). Typically a fraction of the assumptions made for commissioning.
- **Operations**: energy use and subsequent emissions due to the operation of a process (electricity and diesel during coal mining, natural gas for the auxiliary boiler during power plant operations).

All assumptions and data limitations will be noted. All references are listed at the conclusion of the appendix.

Figure A-1 is the main GaBi plan for this study; this specific plan is for the IGCC case with CCS but both are similar. Plans are used in GaBi to assemble unit processes or sub-plans (nested plans) within an LC study. Essentially, plans are the process maps which visually depict a stage or sub-stage in a system. There are several levels of plans: main, second level, third level, etc. The main plan represents the highest level LC in which all other plans are embedded; from the main plan one could click onto a secondary plan (i.e., LC Stage #1 coal acquisition), and from there onto a third level plan (i.e., coal mine construction). The input and output values shown on this plan are based on the reference flow of 1 MWh (3,600 MJ = 1 MWh). Also included in **Figure A-1** are the adjustable parameters considered during the LCI sensitivity analysis for this study (see main report text for results). Specific details on why these parameters are adjustable are included within the following data assumption text.

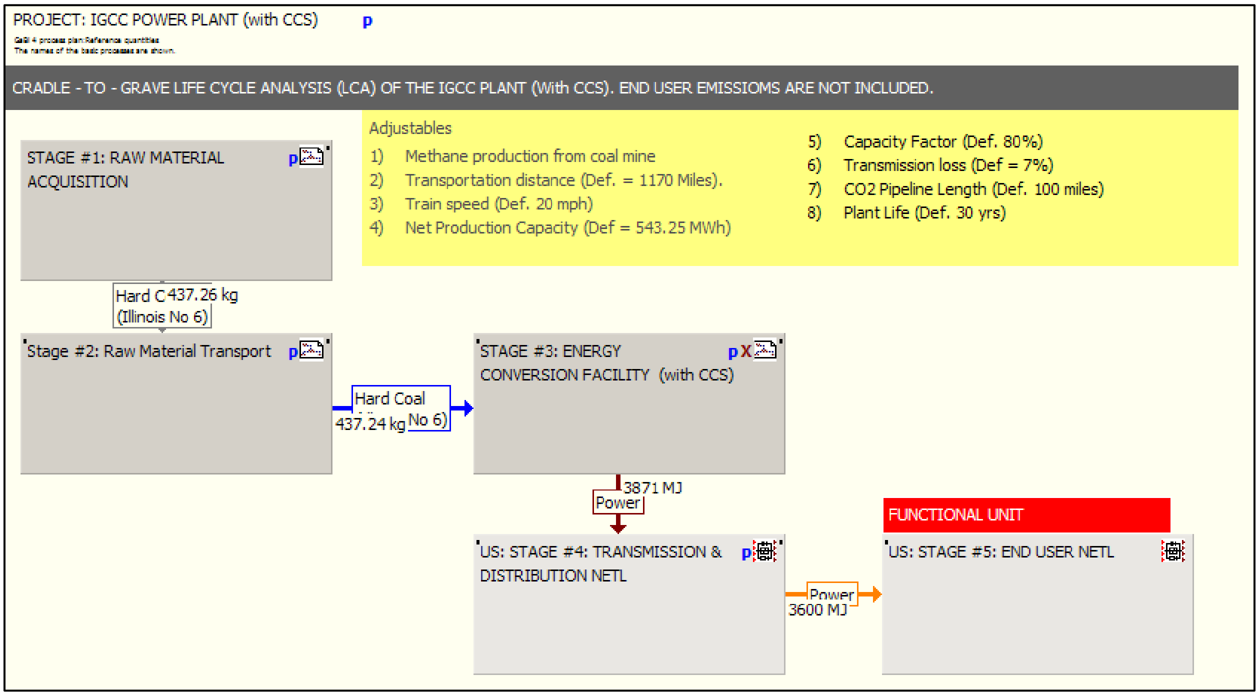

Figure A-1: Main GaBi Plan for the IGCC Case with CCS

A.1.1 Life Cycle Stage #1: Raw Material Acquisition – Coal Mining and Processing

A.1.1.1 GaBi Plan

Figure A-2 is the second level GaBi plan for the Stage #1 coal mining process. For this stage, CH_4 emissions are the only adjustable parameter, meaning that sensitivity analysis can be performed on this parameter within the GaBi modeling framework. The reference flow of this stage is 1 kg of coal produced from the mine. Data assumptions for each input (coal mine operation, coal mine construction, and commissioning/decommissioning) are discussed in the following sections. Water use and emissions are not captured in the GaBi plans; they only show input data that is tracked within the GaBi modeling system. Emissions are considered outputs and therefore are not included. Water use, although an input, is not tracked in the model as no GaBi profiles exist for water use in the model to date. For now, water is inventoried for each stage, when applicable.

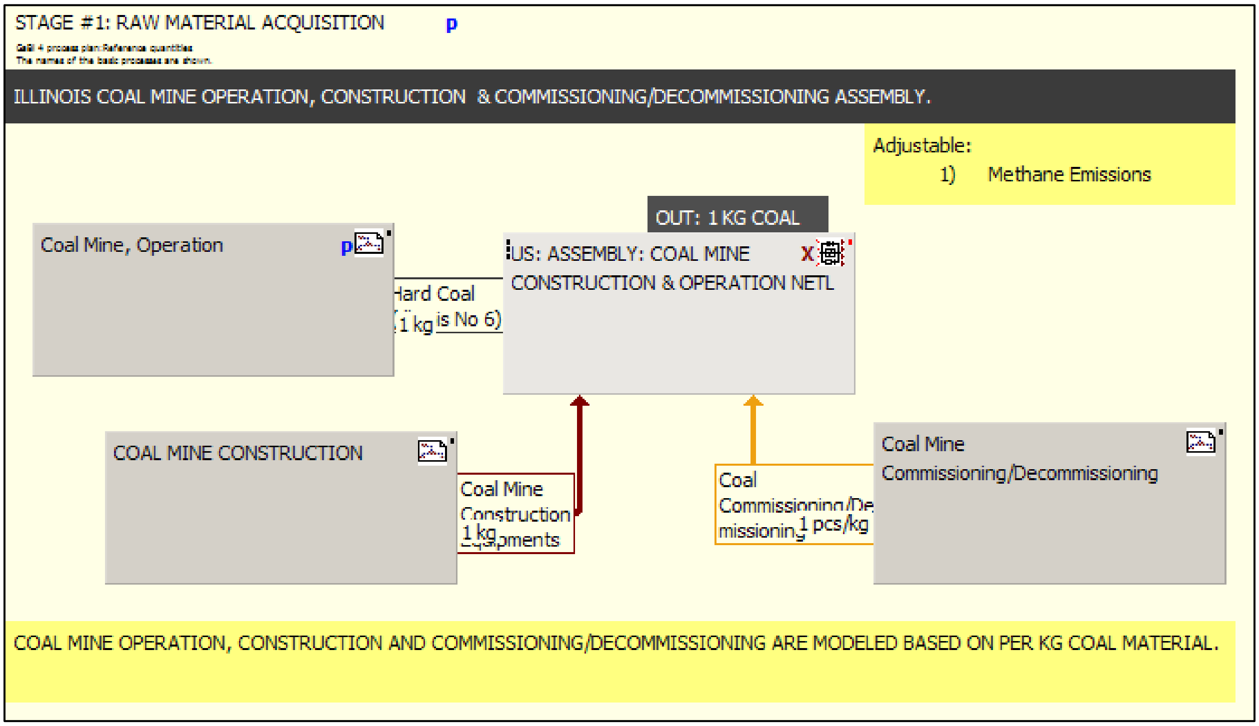

Figure A-2: GaBi Plan for LC Stage #1: Coal Acquisition

A.1.1.2 Commissioning, Installation, and Decommissioning Assumptions

No data were available for the commissioning or decommissioning of the Galatia Mine, so fuel consumption and emissions data were obtained from a draft EIS for the Red Cliff Mine in Colorado (DOI, 2009). The Red Cliff Mine is an underground mine expected to have an annual output of eight million tons, and have a productive lifetime of 20 to 30 years. The EIS provided data for the on-site machinery fuel use and tailpipe emissions (GHG and criteria air pollutants) in Appendix H, Air Quality Analysis Modeling Report (DOI, 2009). Tons of pollutants emitted per year were converted into tons per commissioning by multiplying by 1.5, the length of time expected to complete the commissioning (DOI, 2009). These values were then converted into kilograms and divided by the total expected output of the mine over 30 years, 217,724,337,600 kg, to determine the amount of emissions on a per kg of coal produced basis. Equipment fuel use data, for both gasoline and diesel, were taken from the same data source and calculated on a per-kg of coal produced basis in the same fashion.

The PM emissions were taken from a different location in the same source (DOI, 2009). It was assumed that the value given for $PM_{2.5}$ emissions would encompass all particle matter greater than 2.5 microns, including PM_{10} emissions; therefore the total value for $PM_{2.5}$ was assumed for all PM $\leq$ 10 microns. It was also assumed that the total PM values given included consumption and fugitive dust emissions. The given values were in tons/yr, and were also converted to kg PM/kg coal produced.

The emissions for NH_3 and Hg were calculated using data from two other sources (Battye, Battye *et al.*, 1994; Conaway, Mason *et al.*, 2005). The emission factors for both fuels was given, NH_3 in kg/1000 L of gas (or diesel) (Conaway *et al*. 2005) and Hg in ng/g of gas (or diesel) (Battye *et al*. 1994). Each emission factor was multiplied by the amount of each fuel used during commissioning to get a final value per kg of coal produced.

The values of each fuel and emission for commissioning was then multiplied by 10 percent to account for decommissioning emissions and fuel consumption, a common assumption in the literature (Hill, O''Keefe *et al.*, 1995; Odeh and Cockerill, 2008; Gorokhov, Manfredo *et al.*, 2002). Reliable data for water use during coal mine commissioning and decommissioning was unable to be located and was thus considered a minor data limitation. Water would be used to suppress particulate emissions during construction and decommissioning activities.

Based on the given data assumptions, **Figure A-3** represents the fuel inputs to produce 1 kg of output coal during the commissioning/decommissioning process. **Table A-1** shows the GaBi air emissions for this process, including the emissions profiles for the life cycle of diesel and gasoline.

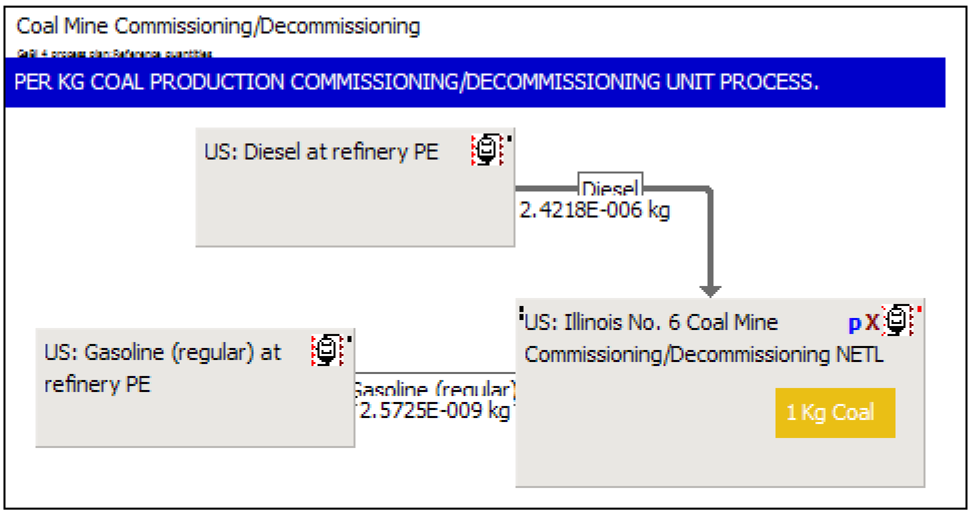

Figure A-3: Fuel Inputs into the Coal Mine Commissioning/Decommissioning Third Level GaBi Plan

Table A-1: GaBi Air Emission Outputs for Coal Mine Commissioning/Decommissioning, Diesel, and Gasoline Inputs (kg/kg coal ready for transport)

Emissions (kg/kg coal ready for transport)	Total	Coal Mine Commissioning/ Decommissioning	Diesel at refinery	Gasoline (regular) at refinery
Lead	4.51E-14	0.00E+00	4.51E-14	6.38E-17
Mercury	4.21E-15	3.86E-16	3.82E-15	6.79E-18
Ammonia	6.68E-12	6.35E-17	6.67E-12	1.62E-14
Carbon dioxide	1.37E-05	1.27E-05	9.97E-07	1.67E-09
Carbon monoxide	3.45E-08	3.30E-08	1.46E-09	1.88E-12
Nitrogen oxides	1.04E-07	1.01E-07	3.10E-09	3.76E-12
Nitrous oxide (laughing gas)	2.51E-10	2.34E-10	1.71E-11	2.32E-14
Sulfur dioxide	4.09E-09	8.25E-11	4.00E-09	5.39E-12
Sulfur hexafluoride	3.80E-18	0.00E+00	3.80E-18	4.74E-21
Methane	1.08E-08	3.78E-10	1.04E-08	1.12E-11
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	4.56E-09	4.56E-09	4.32E-12	4.71E-15
Particulate Matter, unspecified	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dust (unspecified)	3.41E-07	3.41E-07	5.90E-11	6.76E-14

A.1.1.3 Construction Assumptions

The following major equipment/components were needed to operate the modeled coal mine: site paving and concrete, conveyor belt, stacker/reclaimer, crusher, coal cleaning, silo, water treating, continuous miner, longwall miner, and shuttle car systems with replacement. Modeling assumptions for the material use of each component is discussed in the following sections. Overall, the total material inputs needed during the construction process (on a per kg coal output basis) are summarized in **Table A-2**. Also included in **Table A-2** are the GaBi profiles used for the LC assumptions of each material. Although the level of completeness for each profile is different, most are cradle-to-gate. These material inputs are also represented as a GaBi plan view in **Figure A-4**.

Table A-2: Material Inputs and GaBi Profiles used for the Construction of a Coal Mine (1 kg Coal Output)

Material	Amount	Unit	GaBi Assumption
Cold-Rolled Steel	1.4704807E-05	kg	Cold-rolled steel profile – PE
Hot-dip Galvanized Steel	1.5194872E-06	kg	Hot-dip Galvanized Steel profile - WOR
Rubber	4.4476729E-07	kg	Styrene butadiene rubber mix (SBR) - PE
Steel Plate	1.8025590E-04	kg	Steel plates – BF
Concrete	6.0562609E-05	kg	Concrete, ready mixed, R-5.0, (MP-CG)
Rebar	1.4088365E-06	kg	Rebar wire rod, BF – WOR
Polyvinylchloride Pipe	1.2992707E-07	kg	Polyvinylchloride pipe – PE
Steel, Stainless, 316	6.7669300E-08	kg	Steel stainless 316, 2B 80%
Stainless Steel Cold Roll 431	6.7669300E-08	kg	Stainless steel cold rolled – PE
Cast Iron	3.3834650E-07	kg	Cast iron part (Sand casting) - PE
Copper Mix	8.1127506E-09	kg	Copper mix 99.999% - PE
Asphalt	1.1053860E-03	kg	GAB II, Asphalt – DK (Data from DK but profiles from United States)

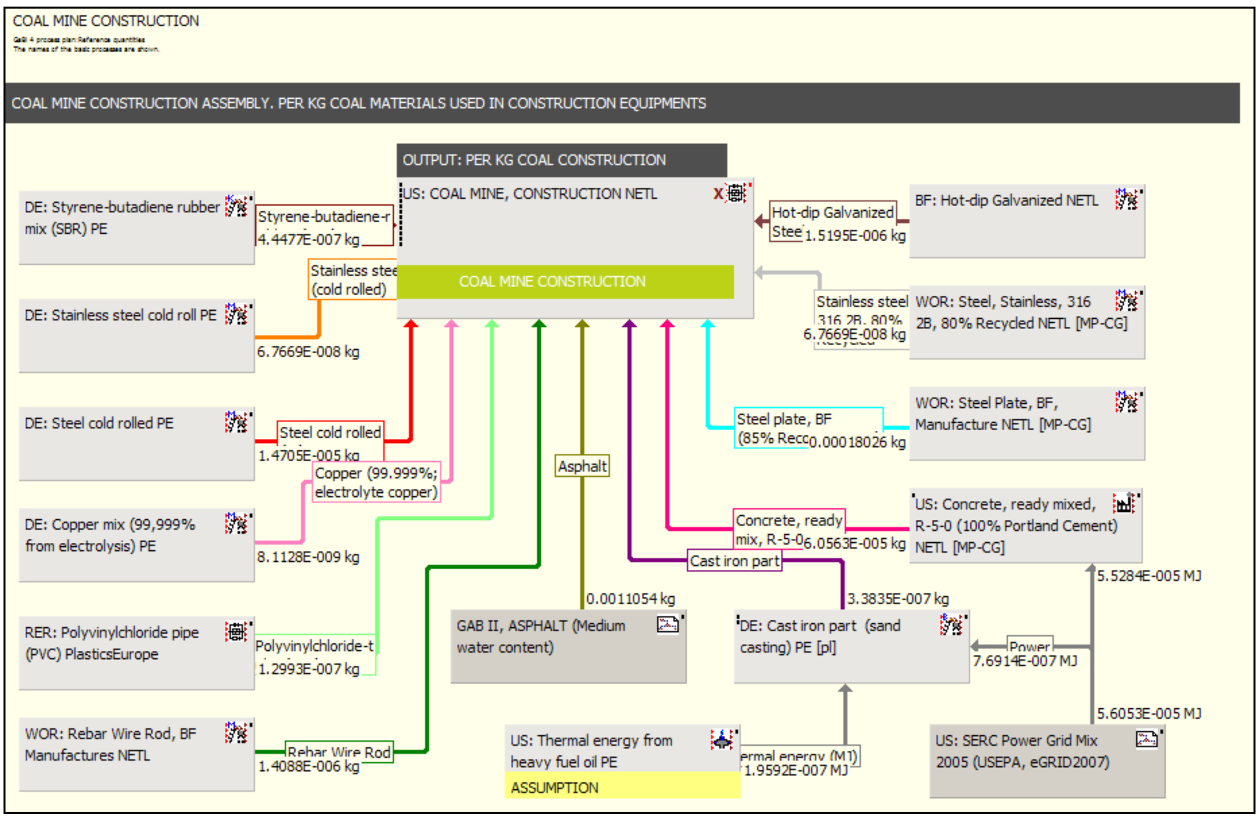

Figure A-4: GaBi Plan View for Material Inputs during Coal Mine Construction

Table A-3a & Table A-3b shows the total air emission for coal construction and the life cycle emission profiles for material inputs.

Table A-3a: GaBi Air Emission Outputs for Coal Construction included Total and Profile Specific Emissions, kg/kg Coal Ready For Transport

Emissions (kg/kg coal ready to transport)	Total	GAB II, ASPHALT (Medium water content)	SERC Power Grid Mix 2005 (USEPA, eGRID2007	BF: Hot-dip Galvanized NETL	DE: Cast iron part (sand casting) PE [pl]	Copper mix (99,999% from electrolysis) PE	DE: Stainless steel cold roll PE	DE: Steel cold rolled PE
Lead	4.77E-10	4.20E-12	5.49E-13	5.55E-12	2.06E-14	9.29E-13	6.14E-14	4.91E-11
Mercury	2.70E-11	3.43E-13	1.55E-13	1.96E-13	7.98E-16	2.11E-16	1.96E-14	6.28E-14
Ammonia	7.36E-10	5.60E-10	5.30E-11	0.00E+00	8.03E-13	2.24E-13	1.01E-12	8.85E-11
Carbon dioxide	2.79E-04	1.74E-05	1.10E-05	1.98E-06	4.15E-07	3.16E-08	3.26E-07	2.72E-05
Carbon monoxide	2.10E-06	3.00E-08	4.56E-09	2.30E-08	5.25E-10	2.99E-11	1.96E-10	2.58E-07
Nitrogen oxides	5.22E-07	6.55E-08	2.14E-08	4.13E-09	3.25E-10	7.17E-11	4.79E-10	5.15E-08
Nitrous oxide (laughing gas)	1.17E-08	3.19E-10	1.46E-10	9.32E-11	5.96E-12	1.38E-12	3.91E-12	1.77E-10
Sulfur dioxide	6.92E-07	9.09E-08	6.26E-08	0.00E+00	2.33E-10	1.14E-10	1.35E-09	3.77E-08
Sulfur hexafluoride	1.34E-13	1.34E-13	7.52E-17	0.00E+00	1.41E-18	1.57E-18	6.97E-18	1.98E-16
Methane	3.94E-07	1.78E-07	1.21E-08	2.80E-09	3.31E-10	4.34E-11	4.11E-10	3.19E-08
Methane (biotic)	3.83E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	3.25E-08	3.68E-11	1.54E-12	1.99E-10	1.11E-14	3.46E-14	2.19E-12	1.55E-12
Particulate Matter, unspecified	3.19E-09	2.56E-10	0.00E+00	2.09E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dust (unspecified)	9.52E-08	9.97E-10	1.19E-09	0.00E+00	6.79E-10	4.66E-11	1.11E-10	1.66E-08

Table A-3b: GaBi Air Emission Outputs for Coal Construction included Total and Profile Specific Emissions, kg/kg Coal Ready For Transport

Emissions (kg/kg coal ready to transport)	DE: Styrene-butadiene rubber mix (SBR) PE	Polyvinylchloride pipe (PVC) PlasticsEurope	US: Coalmine, Construction NETL	Concrete, Ready Mixed, R-5-0 (100% Portland Cement)	US: Thermal energy from heavy fuel oil PE	WOR: Rebar Wire Rod, BF Manufactures NETL	WOR: Steel Plate, BF, Manufacture NETL [MP-CG]	WOR: Steel, Stainless, 316 2B, 80% Recycled
Lead	5.45E-14	1.56E-14	0.00E+00	0.00E+00	2.96E-15	2.76E-12	4.13E-10	0.00E+00
Mercury	4.74E-15	4.14E-14	0.00E+00	0.00E+00	1.37E-17	1.65E-13	2.60E-11	0.00E+00
Ammonia	3.00E-11	1.57E-12	0.00E+00	0.00E+00	1.06E-13	0.00E+00	0.00E+00	0.00E+00
Carbon dioxide	1.38E-06	3.26E-07	0.00E+00	8.39E-06	1.82E-08	1.23E-06	2.09E-04	3.67E-07
Carbon monoxide	3.95E-10	3.97E-10	0.00E+00	1.08E-08	6.70E-12	1.47E-08	1.76E-06	6.57E-10
Nitrogen oxides	1.51E-09	0.00E+00	0.00E+00	2.56E-08	2.08E-11	1.32E-09	3.49E-07	8.34E-10
Nitrous oxide (laughing gas)	2.96E-11	6.20E-19	0.00E+00	0.00E+00	1.59E-13	3.99E-11	1.08E-08	0.00E+00
Sulfur dioxide	1.61E-09	1.26E-09	0.00E+00	1.95E-08	7.69E-11	0.00E+00	4.75E-07	1.69E-09
Sulfur hexafluoride	3.04E-18	0.00E+00	0.00E+00	0.00E+00	7.83E-21	0.00E+00	0.00E+00	0.00E+00
Methane	5.48E-09	3.75E-09	0.00E+00	0.00E+00	1.88E-11	8.51E-10	1.58E-07	0.00E+00
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00	3.83E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	5.74E-13	8.92E-12	0.00E+00	9.44E-10	7.56E-15	2.31E-10	3.10E-08	0.00E+00
Particulate Matter, unspecified	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.45E-10	0.00E+00	0.00E+00
Dust (unspecified)	2.58E-11	0.00E+00	0.00E+00	2.50E-08	3.40E-13	0.00E+00	5.00E-08	4.84E-10

Site Paving and Concrete

Concrete and asphalt material inputs for mine roads and modular buildings/storage facilities were estimated from data reported in two underground mine applications: Sugarcamp Energy, LLC mine (Sugarcamp mine) in Macedonia, Illinois, and Hillsboro Energy, LLC Deer Run Mine (Deer Run Mine) in Montogomery County, Illinois (DNR, 2008). The applications were chosen due to their proximity to the studied mine site. Based on the application for the Sugarcamp mine, approximately 719 acres of the total 1,264 acres at the mine site will be developed for use, whereas the application for the Deer Run Mine estimates that 638.5 acres of the total 803.5 acres at the mine site will be developed (DNR, 2008).

Concrete was needed to build the bases and roofs for office buildings and warehouses as well as tubes for coal storage. Although many more materials would be used in building construction, concrete was listed as a main component in the applications and was therefore the only material considered here. **Table A-4** lists the total amount of concrete specified for each function and mine site. It was assumed that when the applications refer to concrete measured in a yard (yd) it is a cubic yard, based on convention.

Table A-4: Concrete Amounts Specified in the Sugarcamp and Deer Run Mine Applications (DNR, 2008)

Concrete	Sugarcamp Mine Application #382 (pg 421-422)	Deer Run Mine Application #399 (pg 406-407)
Concrete Base (yds^3)	11	11
Concrete Tank (yds^3)	2,094	2,095
Concrete Tube (yds^3)	209	209
Concrete Roof (yds^3)	260	260
Concrete Tube (yds^3)	558	837
Concrete Roof (yds^3)	622	622
Total Concrete (yds^3)	3,754	4,034

A ratio of concrete to acres of developed land was calculated by dividing the total concrete used at each mine by total developed acres. Calculations are summarized in **Table A-5**. The acres developed for the study mine was estimated at 721, and the amount of concrete used for the study mine was converted to kg by dividing the total concrete amount (yds^3 converted to ft^3) by the weight of concrete, $145 lb/ft^3$ and then multiplying by the pounds to kilogram conversion factor (Portland Cement Association, 2008). Concrete used for this study mine is equal to 7,391,888.4 kg (16,296,323 lb).

Table A-5: Data and Calculations for Concrete Needs during Mine Siting

Parameter	Amount	Reference
App. #382 Concrete, yds^3	3,754	Calculated (App #382)
App. #382 Acres Developed	719	Calculated (App #382)
App. #382 Total Concrete , yds^3/acre	5.2	Calculated (App #382)
App. #399 Concrete, yds^3	4,034	Calculated (App #399)
App. #399 Acres Developed	639	Calculated (App #399)
App. #399 Total Concrete, yds^3/acre	6.3	Calculated (App #399)
Average Concrete, yds^3/acre	5.77	Calculated
Study Mine Acres Developed	721	Calculated[1]
Study Mine Concrete, yds^3	4,160	Calculated
Study Mine Concrete, kg (lbs)	7,391,888 (16,296,323)	Calculated

Road asphalt was used to create parking lots and roads. According to the mine applications used, roads are to be constructed of asphalt, however no specification of the asphalt used in given. For this reason, it is assumed that study mine roads are constructed out of asphalt concrete pavement. Roads are estimated to cover approximately 16 acres at the Sugarcamp mine and 46 acres at the Deer Run Mine (DNR, 2008). The estimated amount of road using asphalt, measured in acres, was divided by the total acres developed to give a percentage of asphalt per acre. The Sugarcamp mine had a percentage of asphalt equal to 2.23, while the Deer Run Mine had a percentage equal to 7.20. These were averaged together to give an asphalt percentage for this study of 4.71. To determine the amount of asphalt used in the construction of the roads the total developed acreage of the mine site, 721.43 acres, was multiplied by the study asphalt percentage of 4.71. The total asphalt used for this study mine equals 34 acres. The study mine asphalt amount was converted to square yards and then to cubic yards using the thickness of the road, two ft., stated in the mine applications (DNR, 2008a; DNR, 2008b). The total cubic yards for the study mine is 109,753, which translates to 2,963,338 ft^3. According to the U.S. DOT Federal Highway Administration, asphalt concrete pavement has a total unit weight of 148 lb/ft^3 (DOT, 2002). By multiplying the total cubic feet of concrete at the study mine by the total unit weight of asphalt concrete pavement, a total weight for the study mine asphalt is calculated as 198,933,861 kg (438,574,091 lb). Data and calculations are summarized in **Table A-6**.

[1] Study mine acres developed was based on the coal output of the Galatia Mine versus that of the source data (DNR applications). As these calculations were done at different times, this number is approximately 15 percent different than the acreage used to calculate land use change (based on satellite imagery).

Table A-6: Data and Calculations to Determine Asphalt Needs for Mine Roads and Parking Lots

Parameters	Amount	Reference
App. #382 Asphalt ,acres	16	App #382
App. #382 Acres Developed	719	Calculated (App #382)
App. #382 Percent Asphalt	2.23%	Calculated (App #382)
App. #399 Asphalt ,acres	46	App #399
App. #399 Acres Developed, acres	639	Calculated (App #399)
App. #399 Percent Asphalt	7.20%	Calculated (App #399)
Average Percent Asphalt	4.71%	Calculated
Study Mine Acres Developed	721	Calculated
Study Mine Asphalt ,acres	34	Calculated
Study Mine Asphalt, ft^3	2,963,338	Calculated
Study Mine Asphalt kg (lb)	198,933,861 (438,574,091)	Calculated

Coal Conveyor

A conveyor belt is needed to carry mined coal from an underground longwall mine operation to a coal stockpile on the surface. The conveyor is modeled after the slope conveyor at the Galatia Coal Mine in Galatia, Illinois. This conveyor is 1,554.48 m long and has a 1.2192 m wide steel-cord belt (Roberts & Schaefer, 2007). The belt has a useful life of approximately 20 years (Goodyear, 2008a). Major components of the conveyor belt system include the idler system (frame and brackets on which the belt is carried and the rotating parts [rollers] on which the belt travels), the drive and tail pulleys that move the belt, the steel cord inside the belt, and the rubber compound that surrounds the cord as well as providing a surface to carry the load.

The frame, bracket, and roller specifications for the idler system were all obtained from the Sandvik Mining and Construction Company (2004). There are two individual idler systems– the main idlers that carry the belt and the coal from the mine to the surface and a return idler system that loops below the idlers and carries the belt back to the underground mine. The main idler system modeled is a three-roll inline carry and impact system. The rollers are assumed to be manufactured from cold-rolled steel and have a diameter of 152 mm and a bearing size of 6306. The total main idler system weighs a combined 58.3 kg; the rotating parts make up 24.3 kg, while the frame and brackets (manufactured from galvanized steel) make up 34.0 kg (Sandvik, 2004). The main idler system was assumed to be spaced one meter apart along the entire length of the conveyor belt. The return idler system consists of a single roller manufactured from cold-rolled steel and the frame and brackets, manufactured from galvanized steel. The rollers are the same diameter and bearing size as those used in the main idler. The return idler system weighs 33.9 kg, with the rotating parts being 20.6 kg and the frame and brackets being 13.3 kg (Sandvik, 2004). The return idler systems are assumed to be spaced every three meters, running along the same path as the main idler systems. Based on these assumptions, the rotating parts weigh 6.87 kg/m and the frame and brackets weigh 4.43 kg/m.

This conveyor belt requires both a drive pulley to power the belt and a tail pulley for the belt to return to the mine to carry more coal to the surface. Both the drive and tail pulleys are assumed to be constructed of 100 percent cold-rolled steel. The tail pulley has a weight of 1,023 kg, and the drive pulley weighs 1,044 kg (Sandvik, 2003).

Data for the conveyor belt itself was obtained using Goodyear's Flexsteel Conveyor Belt (Goodyear, 2008a). This belt consists of galvanized steel cords with a nominal 5.2 mm diameter. The cords run the entire length of the belt, spaced every 11.4 mm on center (Goodyear, 2008a). The cord design was based on seven thin steel cables grouped together; seven of these bundles are then wound together to form a 7×7 cord. Representative steel cord (or cable) specifications were obtained from two manufacturers (Lexco, 2006; Loos, 2006); the nearest representative cable diameter was 3/16 in., or approximately 4.76 mm. Each cord has a weight of approximately 9.23 kg/100 m, which was converted to 0.0923 kg/m (Lexco, 2006; Loos, 2006). Spread evenly over the entire 1.2192 m width of the belt, there will be 106 cords running the length of the belt. In order to get the weight of the steel cord per meter of belt, the weight of a single cord (0.0923 kg/m) was multiplied by the number of cords based on the belt width for a value of 9.78 kg/m.

To calculated the total weight of the belt on has to consider the insulating rubber surrounding the steel cords, a diagram of which is shown in Figure A-5: Flexsteel Belt Construction (Goodyear, 2008b) **Figure A-5** (Goodyear, 2008b). The top rubber cover is assumed to be 4.5 mm thick and the bottom cover 1.5 mm thick. The nominal diameter of the steel cables is 5.2 mm, for a total belt thickness of 11.2 mm. The belt weight is the cover weight (7.5 kg/m^2) plus the carcass weight (14.6 kg/m^2), which comes out to 22.1 kg/m^2 (Goodyear, 2008a). The weight of the belt was multiplied by the width of the belt, 1.2192 m, to obtain a value of 26.94 kg/m of belt. The weight of steel cord was subtracted from this value for a total of 17.16 kg of rubber per meter of belt.

Figure A-5: Flexsteel Belt Construction (Goodyear, 2008b)

In addition to the rubber, the following is a summary of the other material inputs described above. The materials manufactured from hot-dip galvanized steel include the steel cord, the idler frame and brackets, and the return idler frame and brackets. The steel cord weighs 9.78 kg/m, the idler frame 34 kg/m, and the return idler frame 4.43 kg/m. Summed, this gives a total of 48.21 kg/m of hot-dip galvanized steel. Cold-rolled steel was used for the idler and return idler rotating parts, the tail pulley, and the drive pulley. Since there is only one of each type of pulley, their weights will be added to the total cold-rolled steel value at the end of the calculations.

To finalize the conveyer belt calculations, the weight of each material was multiplied by the length of the belt to obtain a total weight. The belt has a given length of 1,554.48 m, which was doubled to 3,108.96 m to account for the fact that the belt actually makes a large loop to return to the underground mine. The total weight of rubber for the belt was 17.164 kg/m times 3,108.96 m, or 53,362.52 kg. The weight for hot-dip galvanized steel was 48.214 kg/m times 3,108.96 m, a total of 149,893.99 kg. The weight of cold-rolled steel was 31.17 kg/m times 3,108.96 m added to the weights of the drive and tail pulleys, for a total weight of 98,962.92 kg.

Stacker Reclaimer

A single stacker reclaimer (referred to as a stacker) was modeled, as it is used at the mine site to stockpile the coal coming of the coal conveyor; this coal is referred to as ROM coal. A coal stacker is a piece of equipment used to retrieve and form large piles of ROM coal prior to being fed to the coal sizing and cleaning stages. A stacker uses a boom, cantilever, and conveyor system for moving coal. It is assumed that the entire machine will be constructed from steel. The conveyor belt materials will be neglected because the belt itself makes up only a small fraction of the machine's total weight. The estimated weight of the stacker is 450,000 kg, based on weight specifications of the Xstrata Rolleston Coal Stacker (Gay, 2006).

Coal Crusher

The coal crushing facility is an above ground process that reduces the size of ROM coal. The coal is conveyed from the stacker into the crushing facility, at which point the size of the coal is reduced before sending it to the coal cleaning facility for further preparation. The coal crushing facility in this study is modeled after an Australian coal crushing facility (Leed, 2006). The crushing facility in Australia was constructed to incorporate a reinforced earth wall behind the primary crusher. Others operations included in the construction were secondary and tertiary crushing equipment, product screening and stockpiling operations, an ROM pad, conveyor footings, a fine sampling area, stair footings, a pedestrian bridge, and associated earthworks for concrete works. Material requirements for the Australian facility included 250 metric tonnes (275 short tons) of steel rebar and 1,500 m^3 (53,000 ft^3) of concrete.

The facility located at the Illinois based underground mine is assumed to use approximately the same amount of concrete and rebar to construct its facility. The concrete pad, assumed to be Portland cement, will be constructed to have a compression rating of 4,000 psi and an average density of 1,506 kg/m^3. This density was multiplied by the volume of cement assumed (1,500 m^3) to get an estimate of 2,259,000 kg of concrete for construction. Additionally, the weight of rebar was also converted to kg for a total of 250,000 kg (Leed, 2006).

It was assumed that a primary and secondary coal crusher would be operational within the crushing facility (two in total), based on the input sizes and the availability of model weights compared to the coal mine output. The primary coal crusher was modeled using Pennsylvania Crusher's Bradford Breaker model 14 ft.×28 in., which weighs approximately 182,200 lb (Penncrusher, 2009). The secondary crusher will be modeled after Pennsylvania Crusher's Reversible Impactor Model CA 10-60, and weighs approximately 106,000 lb (Penncrusher, 2008). Both of these crushers are manufactured from heavy duty steel plate. Combined, these crushers weight 288,000 lb, which was then converted to 130,635 kg.

Coal Cleaning

This process encompasses all of the materials that are required in the construction of a steel building to be used to house coal cleaning equipment; a steel building with a reinforced concrete slab as a foundation. The concrete slab will also serve as the first floor of the building. Carbon steel I-beams (high-strength, low-alloy) will form the exterior frame of the building as well as each of the other 5 floors, plus the roof (Saginaw, 2009). The walls and roof of the facility will be constructed out of zinc-galvanized steel panels (Bay Area Rapid Transit, 2004; Buildings Direct, 2009; Steel Building, 2009; Engineers Edge, 2009).

The exterior of the building will be 100 ft. long × 60 ft. wide. Vertical I-beams will be spaced every 20 ft. along all four walls. Horizontal I-beams will form the floors from the second level up to and including the roof (six total levels). Each level will be 14 ft. tall, for a total building height of 84 ft. The I-beams for the floor will be spaced every 20 ft., running horizontally both the length and width of the building. The weight of the steel for the I-beams will be determined by taking the average of four beams with a depth of 12 inches (in.). A cross-sectional diagram of the style of I-beam can be seen in **Figure A-6**.

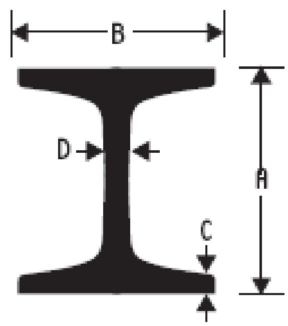

Figure A-6: Cross-sectional Diagram of an I-beam

The exterior of the building, all four walls and the roof, will be clad in 26-gauge zinc-galvanized carbon steel panels (Buildings Direct, 2009; Engineers Edge, 2009; Steel Building, 2009). The zinc is a layer with a volume of approximately 1.25 ounces per square ft (oz/ft^2) of steel panel (Bay Area Rapid Transit, 2004).

The foundation of the building, which will also serve as the ground floor, will be constructed using a 4,000 psi mix of concrete. The concrete foundation will be reinforced by size #4 carbon steel rebar running horizontally over both the length and the width of the concrete. The rebar will be evenly spaced every 12 in. in both directions, and has a cross-sectional area of 0.20 in^2 (CRSI, 2008). The perimeter of the slab must be located below the frost line, which is located 21 in. below ground level at the mine location (Weather Bureau, 2008). The exterior of the concrete slab will extend an additional 6 in. below the frost line and will be 18 in. thick around the perimeter. The interior of the concrete slab will be 1 in. thick.

The flooring for each level of the building is assumed to consist of steel grating. This weight is excluded from these calculations due to the assumption they will be balanced by the sections of the interior I-beams that will be removed for stairways and to accommodate large pieces of equipment.

The weight of each material used in the coal cleaning facility was calculated separately. The materials were cold-rolled steel for the I-beams and the exterior paneling, zinc for the galvanization of the paneling, rebar for reinforcing the concrete foundation, and concrete for the building foundation.

Rebar will be spaced evenly every 12 in. along the width and length of the concrete foundation. Since the foundation will only be 12 in. thick, there will be only once grid-like layer of rebar. There will be 58 bars running the length of the foundation and 98 running the width because in each case, the first bar will be laid 12 in. in from the perimeter of the concrete. There will be a total length of 11,680 ft. of rebar, all with a nominal area of 0.20 in^2 (CRSI, 2008). Multiplying these two values gives a total volume of 15.9 ft^3 of rebar. Basic cold-rolled steel has a density of 0.284 lb/in^3 (Metal Suppliers Online, 2009), which calculates to a total rebar mass of 7,816 lb. required for this building.

The exterior portion of the concrete foundation is 100 ft. long × 60 ft. wide by 18 in. thick, and extends 27 in. into the ground. Converting these values to feet and multiplying to account for all four sides of the building gives a total of 1,080 ft^3 of concrete for the exterior foundation. The volume of concrete required for the remaining interior foundation was calculated by multiplying the length of the foundation, minus the 18 in. width of the exterior, by the width of the foundation, minus the 18 in. width of the exterior, and the thickness (12 in.) of the interior concrete slab. This value, 5,762 ft^3, was added to the exterior volume for a total volume for the foundation of 6,842.25 ft^3. The volume of the rebar above was subtracted from the total volume of the foundation to determine the actual volume of concrete in the foundation, which comes out to be 6,826 ft^3. Multiplied by the density of 4,000 psi concrete, 145 lb/ft^3, gives a total weight of 989,817 lb.

The exterior framework of the building is constructed of vertical I-beams spaced every 20 ft. along all four sides. Each beam is 84 ft. tall. The weight per foot of beam was calculated by taking the average weight of four 12 in. deep I-beams. This average weight was calculated as 39.40 lb/ft (Saginaw, 2009). Both the front and rear walls will consist of six vertical beams, for a total weight of 19,857.60 lb. for each side. Each side wall has four vertical beams, but the outer ones have already been accounted for in the calculations of the front and rear walls. Taking the average beam weight of 39.4 lb/ft. times the 84 ft. height of each beam gives a total of 6,619 lb. for each side wall. Combining the calculations for the front, back, left, and right walls gives a combined total of 52,954 lb. of cold-rolled steel for the building's I-beams.

The I-beams that will form the basis for each level within the building were calculated in a fashion similar to that of the exterior framework. Each floor consists of four 100-ft. long beams and six 60-ft. long beams. The average weight of these beams is 39.4 lb/ft (Saginaw, 2008). The four 100-ft. long beams weigh a total of 15,760 lb., while the six 60-ft. long beams weigh 14,184 lb.; combined, the I-beams for each level consist of 29,944 lb. of cold-rolled steel. The weight for each level is multiplied by six because there are six levels of horizontal I-beams in the building. The total weight for these I-beams is 179,664 lb.

The steel panels for the exterior covering of the building consists of 26-gauge galvanized steel sheets (Buildings Direct, 2009; Steel Building, 2009), which are 0.0179 in. thick (Engineers Edge, 2009). The total surface area to be covered was calculated by multiplying the area of the large sides of the building (100 ft. long by 84 ft. high) by two, multiplying the area of the smaller sides (60 ft. long by 84 ft. high) by two, and adding both to the area of the roof (100 ft. long by 60 ft. wide). The result was 32,880 ft^2, which when multiplied by the thickness of the steel sheets gives a volume of 49.05 ft^3, the amount of steel for the paneling. The volume was converted to cubic inches and then multiplied by the density of cold-rolled steel, 0.284 lb/in^3 (Metal Suppliers Online, 2009). The weight of cold-rolled steel for the panels is 24,069 lb.

The final material for the coal cleaning facility construction is the zinc for galvanization of the steel panels. This coating is 1.25 oz/ft^2 thick (Bay Area Rapid Transit, 2004). The coating thickness was multiplied by the total surface area of the building, 32,880.00 ft^2, for a total of 41,100 oz of zinc. Adding the weight of the steel panels and the zinc will result in a galvanized steel weight of 26,638 lb.

The final step was to convert the weights of each material to kilograms. Cold-rolled steel was used in the I-beams for the framework of the building, the I-beams for each floor. The I-beams weighed 105,514 kg. The galvanized steel panels weighed 1, 2083 kg. The rebar for reinforcing the concrete foundation weighed 3,545 kg. Finally, the concrete for the foundation itself weighed 448,973 kg.

Coal Loading Silo

This process encompasses the total amount of steel necessary to construct a silo that stores the coal ready to be loaded into rail cars for transportation to the power generation facility. The silo is assumed to be constructed entirely of cold-rolled steel. When an empty unit train arrives to be loaded, a chute on the bottom of the silo is opened, releasing the coal to fill the rail car. The silo was modeled after an advertisement for a raw coal silo manufactured by George Third & Sons (George Third & Son, 2006). After unit conversion and scaling to match Galatia Mine's estimated average operational output, the silo was assumed to be 24.38 meters (m) high, 12.19 m in diameter, and weighed 294.84 tonnes (empty), which is the weight of cold-rolled steel for construction of the silo (George Third & Son, 2006).

Wastewater Treatment Facility Construction

The wastewater treatment facility for the study consists of a series of sedimentation ponds that receive stormwater flows from coal storage areas, refuse storage areas, and other surface operations across the mine site. The wastewater treatment facility does not receive discharge water from the coal mine or the coal cleaning process. Note that water treatment for the coal cleaning process consists of a slurry cell that is used to facilitate re-use of water within the coal cleaning cycle; no discharge from the slurry cell occurs. Characteristics of the wastewater treatment facility, including sizing of sediment ponds and details about their operation, were gathered from documentation for a proposed expansion of Deer Run Mine (Hillsboro Energy, 2007; DNR, 2008). To ensure that these assumptions were reasonable, they were cross-checked with the Galatia Mine staff and revised as needed.

The wastewater treatment facility includes approximately 15 acres of storm water retention ponds. These ponds are lined using compacted sediments, which were assumed to be present on site. Water flow into and out of ponds is facilitated by a series of earthen channels/drainages, as well as PVC piping with associated pumps and cement lined outfall/discharge structures.

Pumps and Pipes

Pumps are required to convey a portion of the flow into and out of the water treatment facility. For the purposes of this study, it was assumed that 20 percent of maximum stormwater flows would require pumps, and scaled pump installation to that amount. This resulted in a maximum pump capacity requirement of 169,927 gallons per minute (gpm). Assuming that this flow would be carried using 5,000-gpm pumps, a total of 34 pumps would be necessary to convey maximum storm flow.

Data for the weight and materials used for a pump were taken from manufacturer literature (Power Prime Pumps, 2008). The weight of a representative pump was obtained from a table listing the weights of various pumps, and a skid assembly of 7,900 lb was used from a 5,000 gpm DV-300 pump. Each pump was constructed of 316 stainless steel (impeller and wear plates), 431 stainless steel (shaft), cast iron (much of the body and framework), and hot-dip galvanized steel (skid). Based on schematics, it was estimated that each pump would include, by weight, 10 percent 316 stainless steel, 10 percent 431 stainless steel, 50 percent cast iron, and 30 percent hot-dip galvanized steel. Using the pump weight of 7,900 lb, each pump would include 790 lb of both 316 and 431 stainless steel, 3,950 lb of cast iron, and 2,370 lb of hot-dip galvanized steel. Multiplying by 34 pumps and converting to kilograms gives a total of 12,178.3 kg of 316 stainless steel, 12,178.3 kg of 431 stainless steel, 60,891.5 kg of cast iron, and 36,534.9 kg of hot-dip galvanized steel.

Pumped flows would be conveyed within either 4 in. or 8 in. PVC pipes. Based on the design of the Deer Run facility and anticipated proximity to stockpile areas, we estimate that a total of 8,500 ft of 4 in. and 3,500 ft of 8 in. schedule 80 PVC pipe would be required. Each diameter pipe was multiplied by the weight of PVC per 100 ft. (275 lb/100 ft for the 4 in., 805 lb/100 ft for the 8 in.) and then converted to kilograms. This would result in a mass of 10,603 kg of 4 in. pipe and 12,780 kg of 8 in. pipe, for a total of 23,383 kg of PVC required.

Cement Structures

Based on the design of the Deer Run facility, cement would be used for water flow dissipating structures and for a limited amount of canal lining. Based on 12,500 ft^2 of cement at an average thickness of 1.5 ft., it is estimated that 18,750 ft^3 of cement would be required. Assuming a density of 94 lbs/ft^3 for Portland cement, 799 tonnes of cement was calculated.

Wiring

Wiring will be used primarily to supply electricity to pumps, although we also assume that wiring would supply minor additional loads such as facility lighting. It was assumed that operations for the facility would be housed separately, with operations for the remainder of the mine. Wiring lengths were calculated based upon the design of the Deer Run facility and the anticipated proximity of stockpile areas to the treatment facility (Hillsboro Energy, 2007). here were calculated to be 12,000 total ft. of piping, so the length of wire necessary to power the pumps was assumed to be half of the required length of pipeline, or 6,000 ft. An additional 20 percent of total wire length was included in the assumed value to support lights and other auxiliary uses. The 20 percent was rationed 20/80 into two wiring types – 2-strand gauge 1 wire (e.g. gauge 1 / 2) and gauge 12 / 3, respectively. Herein, 6,000 ft of gauge 1 / 2 wire would be required for pumps, 240 ft for auxiliary wiring, and an additional 960 ft of gauge 12 / 3 wire for auxiliary wiring. The gauge 1 / 2 wire has a length of 3.947 ft. per pound of wire (ft/lb) per strand, while gauge 12 / 3 wire is 50.59 ft/lb (Davis, 2007). Each wire was divided by its length per pound and then multiplied by the number of strands in the wire. After conversion to kilograms, this gives 1,379 kg of gauge 1 / 2 wire for the main pump wiring, 55 kg of 1 / 2 wire for auxiliary wiring, and 26 kg of 12 / 3 wire for auxiliary wiring. Since all wiring is assumed to be copper, a total mass of approximately 1,460 kilograms was calculated.

Other Materials

Clay/sediment lining would be required for the proposed sedimentation ponds. It was assumed that these materials would be available on site, and could be recycled from the pond-digging process. It was further assumed that remaining spoils from pond construction would be used as berms around the ponds to provide flood flow protection, or for grading and fill purposes during construction of other facilities at the mine site.

Final Totals

In total, for the construction of the waste water treatment plant, there will be:

- 12,178.3 kg of 316 stainless steel.
- 12,178.3 kg of 431 stainless steel (represented in GaBi as stainless steel cold roll).
- 60,891.5 kg of cast iron.
- 36,534.9 kg of hot-dip galvanized steel.
- 23,383.0 kg of polyvinylchloride piping.
- 799,456.6 kg of Portland cement.
- 1,460.0 kg of copper.

Continuous Miner

The construction of a single continuous miner was based on specifications for the size and weight of continuous miners from the Bucyrus International company (Bucyrus, 2008). According to the Illinois DNR, the Galatia Mine coal seam thickness for ranges from 84 to 108 inches (DNR, 2006). Based on this information, the 25M-2 Bucyrus Continuous Miner was selected as the reference model because it can operate in seam heights of between 44 and 114 inches (Bucyrus, 2008).

This model has a weight of 56.7 tonnes (Bucyrus, 2008). This value was converted to 56,700 kg. According to page four of the brochure, under the heading “Weight,” the main frame of the miner is constructed from a thick steel plate. Steel is assumed to account for the majority of the weight of the continuous minor.

The hydraulic fluid and cutting head’s teeth (tungsten carbide steel) will last the entire life of the continuous miner’s operational life (will change upon more information or consideration). As delivered to the mine site, a continuous miner includes hydraulic fluid and cutting teeth. These two components are part of the entire construction weight; however, material profiles for hydraulic fluid and tungsten carbide steel are not included in this unit process. Other material components of the continuous miner are assumed to have a negligible contribution to the LC burdens of the continuous miner and are thus not included in this unit process.

Longwall Miner

The complete longwall mining system includes the shear head, roof supports, armored force conveyor, stage loader, and mobile belt tailpiece. The longwall system includes a specific number of roof supports depending on the length of the roof support shields. The roof supports include the stage loader, armored force conveyor, and the mobile belt piece. The shear head is then connected to the roof supports to operate on the track system that is also part of the roof support system.

All components of the longwall miner system are assumed to be constructed from steel plates. The weight of each component, except for the shields, was taken from e-mail communication with Cas Bruniany of Joy Mining Machinery (Joy Mining Machinery, 2008). The weights were:

- Shearer – 50 to 75 tons.
- Armored Face Conveyor.
    - Head Drive – 60 to 70 tons.
    - Tail Drive – 40 to 50 tons.
    - Line Pans – 2.5 tons each.
    - Stage Loader – 80 to 100 tons.

Also according to Bruniany, the expected lifetime of these pieces of equipment is between ten and fifteen years.

The weights of the shields were determined to be 28.2 short tons (Bryja, Conklin *et al.*, 2004). The weight of each component was averaged between the minimum and maximum values to get values of 62.5 tons for the shearer, 28.2 tons for the shields, 65.0 tons for the head drive, 45.0 tons for the tail drive, 2.5 tons for the line pans, and 90.0 tons for the stage loader.

There is one of each component in the longwall miner system except for the shields and line pans. It is assumed that the face of the longwall mine is 1,000 ft. long. The number of shields and line pans for the mine is 176 each (Joy Mining Machinery, 2008). This value was taken from a longwall mine installation that commenced production in 2007. The mine face at the representative mine is 1,000 ft. long, therefore, our mine face is assumed to use the same number of shields and line pans. This gives a total weight for the shields of 4,963.2 tons and 440.0 tons for the line pans.

All of the various longwall miner system components added together give a total weight of 5,665.7 short tons. This value was converted to 5,139,836.58 kg. This is the total weight of steel plate that is necessary to construct the longwall miner system.

Shuttle Car

This process encompasses the materials that are used in the construction of one shuttle car to be used to haul coal from the working mine face to the conveyor belt. Data for the shuttle car was taken from the Phillips Machine Service Manufacture for Shuttle Car models FC12, FC16, FC20, and FC25 (Phillips Machine Service, 2007). The shuttle car is assumed to consist of steel, with only negligible amounts of rubber for the four tires. These cars are powered by batteries that run motors for the pump, conveyor system, and traction systems and can handle payloads up to 19 metric tonnes. Batteries for the car were not separated from the overall weight of the car and, as a result, battery weight is included in the total weight of steel required for the shuttle car. This is a data limitation. The weights of four different sizes of shuttle cars from Phillips Machine Service were obtained and averaged. The cars ranged in capacity from 7.2 cubic meters to 16.1

cubic meters. Each car has an empty weight between 24.5 and 32.7 metric tonnes. These minimum and maximum values were averaged to calculate an average of 28.6 metric tonnes, the empty weight of a single shuttle car.

Continuous Miner, Longwall Miner, and Shuttle Car Replacement

The number of each piece of equipment was based on information for the Galatia Mine; according to the Illinois DNR, there are nine continuous miners and three longwall miner units in the representative mine (DNR, 2006). The conveyor system was modeled after the 5,100-ft. long slope conveyor at Galatia, so there is only one of them constructed (Roberts & Schaefer Company, 2007). Finally, it was assumed that there is a two-to-one ratio of shuttle cars to continuous miners, for a total of 18 shuttle cars.

The second part of the assembly of the underground coal mine was estimating the expected lifetime of each pieces of equipment. The lifetime of the continuous miner and longwall miner unit was estimated using information obtained via personal communication with Cas Bruniany (Bruniany, 2008). The expected lifetime for both of these pieces of equipment is 15 years. In a document for their Flexsteel conveyor system, Goodyear states that their belts are expected to last for 20 years (Goodyear, 2008b). Finally, the shuttle cars have an estimated lifetime of 12 years (Australian Taxation Office, 2008).

Based on a study period of 30 years, the continuous miners and longwall miner units have a replacement rate of 2.0, the conveyor system 1.5, and the shuttle cars 2.5.

A.1.1.4 Operation Assumptions

This process covers the energy needs and emissions associated with the production of coal during operation of the coal mine, from resource extraction through the boundary for LC Stage #2; again, all data inputs for this stage were based on the reference flow of 1 kg of fully processed (output) coal over the 30-year study lifetime. Considered are the consumption of electricity, consumption of diesel, emissions of CH_4 associated with off-gassing from the coal/coal mine, PM emissions associated with fugitive coal dust, water input flows required for mining and cleaning operations, wastewater flows, and emissions of criteria air pollutants, as well as emissions of Hg and NH_3.

Operations of the coal mine were based on operation of the Galatia Mine, which is operated by the American Coal Company and located in Saline County, Illinois. Sources reviewed in support of coal mine operations include Galatia Mine production rates, electricity usage, particulate emissions, CH_4 emissions, wastewater discharge permit monitoring reports, and communications with Galatia Mine staff. When data from the Galatia Mine were not available, surrogate data were taken from other underground mines, as relevant.

Electricity is the main source of energy for coal mine operations, and use for this model was estimated based on previous estimates made by EPA for electricity use for underground mining and coal cleaning at the Galatia Mine (EPA, 2008d). The LC profile for electricity use is based on eGRID2007. The Emissions and Generation Resource Integrated Database (eGRID) is a comprehensive inventory of environmental attributes for electric power systems; the current version of eGRID was updated in January 2009 and is based on 2005 data (EPA, 2009). Although no data were found that estimated the diesel fuel used during mining operations, it was assumed that some diesel would be used to operate trucks for moving materials, workers, and other secondary on-site operations. Therefore, diesel use was estimated for the Galatia Mine from 2002 U.S. Census data for bituminous coal underground mining operations and associated cleaning operations (U.S. Department of Commerce, 2004).

Emissions of criteria pollutants were based on emissions associated with the use of diesel. EPA Tier 4 diesel standards for non-road diesel engines were used, since these standards would go into effect within a couple years of commissioning of the mine for this study (EPA, 2004). Diesel is assumed to be ULSD (15 ppm sulfur). Emissions of Hg and NH_3 from diesel combustion were estimated from other sources and calculated in the same fashion as for diesel used during commissioning (Battye, Battye *et al.*, 1994; Conaway, Mason *et al.*, 2005).

In addition to combustion, other sources of PM and CH_4 existed during coal mine operations. PM emission inventory includes those due to the combustion of diesel, as well as fugitive coal dust from the mining process. Total coal dust emissions from the Galatia Mine were used based on EPA (2005) data for the mine, and were normalized to the reference flow (EPA, 2005b). Coal mining accounts for approximately 30 percent of CH_4 emissions in the United States, with underground mines contributing the largest share (EPA, 2008e). During coal acquisition, CH_4 is released during both the underground coal extraction and the post-mining coal preparation activities. From the EPA inventory of GHG emissions from 1990 through 2006, 90 percent of CH_4 emitted from underground mining was a result of coal extraction, while the remaining 10 percent was emitted during post-mining activities (EPA, 2008e). An average of CH_4 emission estimates for the Galatia Mine (EPA, 2008d) were added to CH_4 combustion emissions for this process. Due to the uncertainty in CH_4 emission estimates, the large global warming potential (GWP) of CH_4, and the ability to capture and use or sell CH_4 for on-site energy, the amount of CH_4 released is included as an adjustable parameter in this process. Sensitivity analysis results are included and discussed in the main report text.

Water use was estimated by Galatia Mine staff (Personal Communication 2009), and wastewater data were taken from available National Pollutant Discharge Elimination System permit reporting documentation for Galatia Mine from 2005-2008 (EPA, 2008c). **Figure A-7** shows the third level GaBi plan view for energy inputs during coal mine operations; water used in coal mining is assumed to be resource (ground or surface water). It is not specifically tracked in GaBi and therefore is not included in the plan. **Table A-7** shows the total GaBi emission outputs for coal mine operation and the additional life cycle emissions associated with electricity and diesel production.

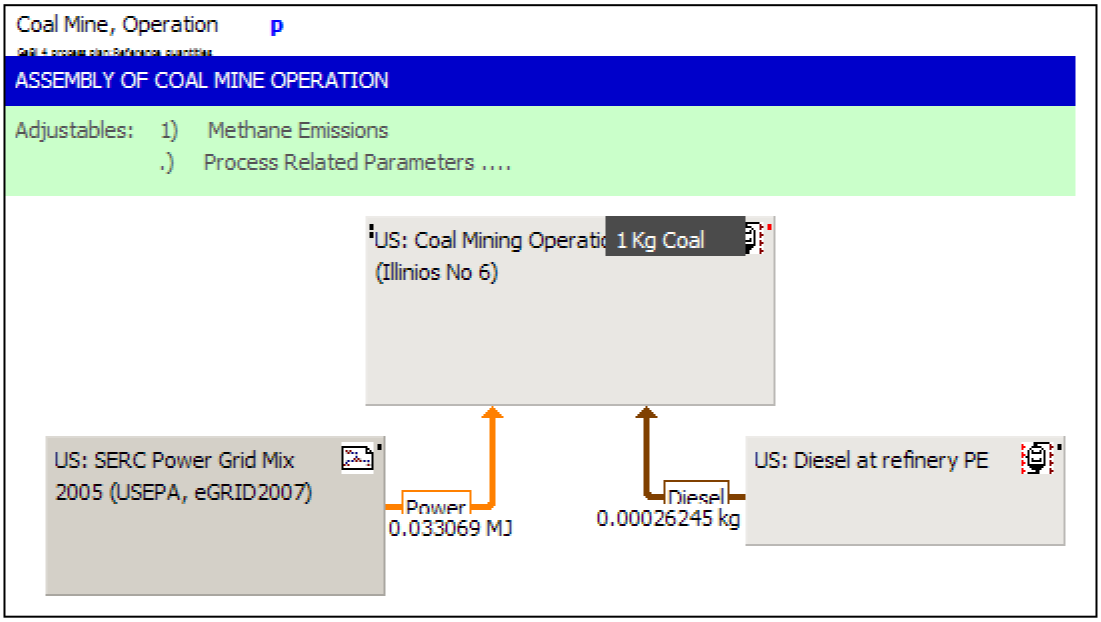

Figure A-7: Coal Mine Operations Fuel Inputs

Table A-7: GaBi Air Emissions for Coal Mine Operations, Electricity, and Diesel Use, kg/kg Coal Ready for Transport

Emissions (kg/kg coal ready to transport)	Total	SERC Power Grid Mix 2005 (USEPA, eGRID2007)	Coal Mining Operation (Illinios No 6)	Diesel at refinery PE
Lead	3.29E-10	3.24E-10	0.00E+00	4.89E-12
Mercury	9.19E-11	9.14E-11	4.08E-14	4.14E-13
Ammonia	6.60E-08	3.12E-08	3.40E-08	7.23E-10
Carbon dioxide	7.45E-03	6.51E-03	8.29E-04	1.08E-04
Carbon monoxide	7.29E-06	2.69E-06	4.44E-06	1.58E-07
Nitrogen oxides	1.35E-05	1.26E-05	5.10E-07	3.36E-07
Nitrous oxide (laughing gas)	1.09E-07	8.62E-08	2.13E-08	1.85E-09
Sulfur dioxide	3.74E-05	3.69E-05	0.00E+00	4.34E-07
Sulfur hexafluoride	4.48E-14	4.44E-14	0.00E+00	4.12E-16
Methane	7.57E-03	7.14E-06	7.56E-03	1.12E-06
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	2.39E-07	9.08E-10	2.38E-07	4.68E-10
Particulate Matter, unspecified	1.27E-06	0.00E+00	1.27E-06	0.00E+00
Dust (unspecified)	7.07E-07	7.01E-07	0.00E+00	6.39E-09

A.1.2 Life Cycle Stage #2: Raw Material Transport – Coal Transport

In Stage #2 it was assumed that the mined coal was transported by rail from the coal mine in southern Illinois to the energy conversions facility located in southwestern Mississippi, an assumed round trip distance of 1170 miles. For this study, a unit train is defined as one locomotive pulling 100 railcars loaded with coal; the locomotive is powered by a 4,400 horsepower diesel engine (General Electric, 2008) and each car has a 91 tonne (100-ton) coal capacity (NETL, 2010).

A.1.2.1 GaBi Plan

Figure A-8 shows the second level plan for this stage. Commissioning /decommissioning is not included in this stage; it can be assumed that the energy used to commission the rail line, unit train, or locomotive would be included in the LC profile of the materials. The reference flow of this stage is 1 kg of transported coal (coal cargo). Several adjustable parameters are listed here for consideration during sensitivity analysis; below the plan is a screen shoot highlighted the adjustable parameters listed.

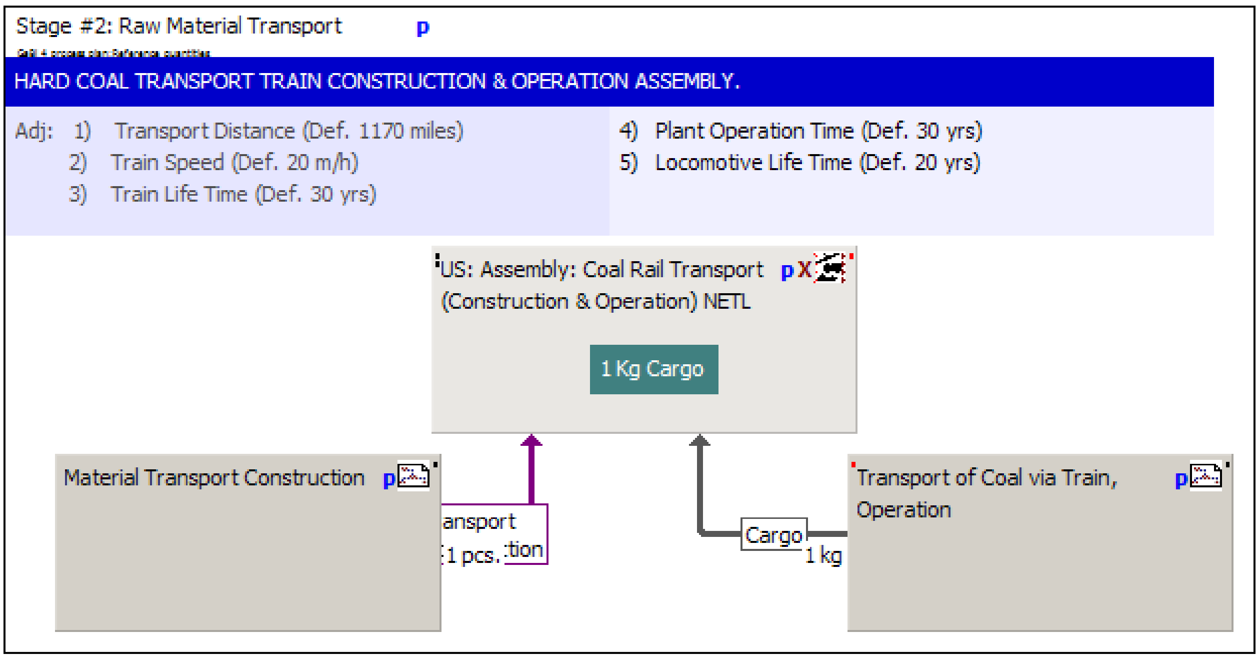

Figure A-8: Second Level GaBi Plan: Stage #2 Train Transport

A.1.2.2 Construction Assumptions

Figure A-9 shows the third level plan for train construction. For this study, a unit train consists of 100 rail cars and five locomotives. **Table A-8** shows the total GaBi air emission outputs for Stage #2 construction and the additional life cycle emission profiles of material inputs for this stage, all on a kg/kg coal delivered to the plant basis.

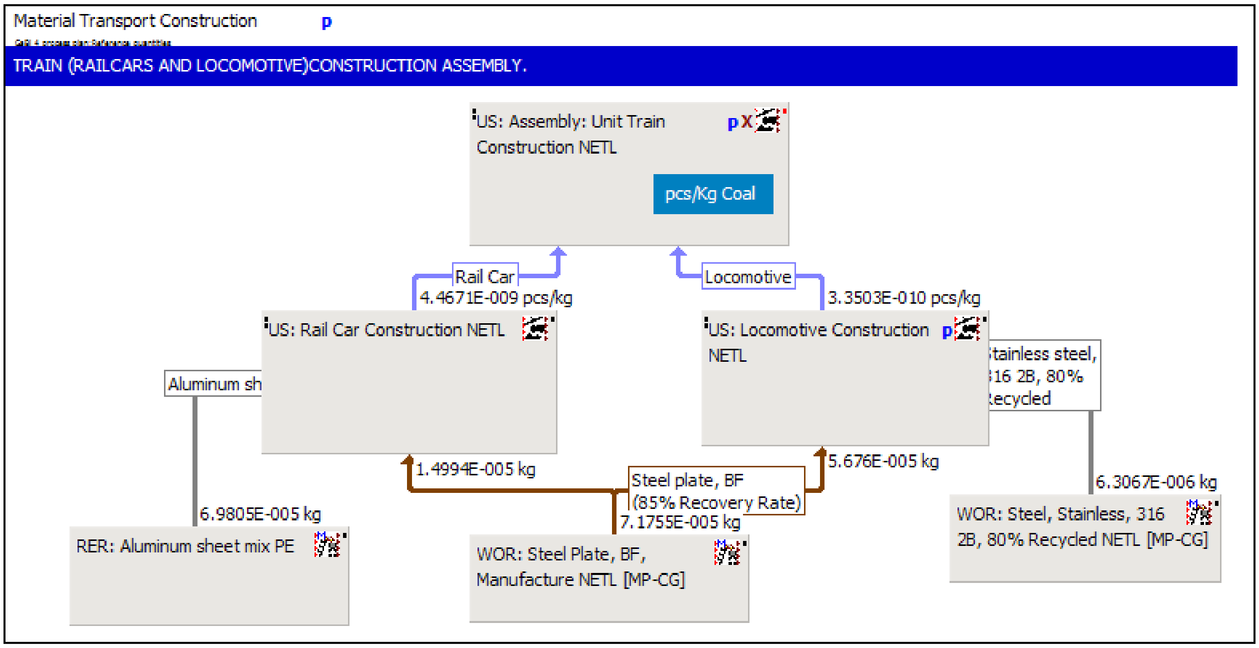

Figure A-9: GaBi Plan for Train Construction

Table A-8: GaBi Air Emission Outputs for Stage #2 Construction and Material Inputs, kg/kg Coal Delivered

Emissions (kg/kg coal delivered)	Total	Aluminum sheet PE [pl]	Steel Plate, BF, Manufacture	Steel, Stainless, 316 2B, 80% Recycled
Lead	2.93E-10	1.28E-10	1.65E-10	0.00E+00
Mercury	2.07E-11	1.04E-11	1.03E-11	0.00E+00
Ammonia	2.97E-09	2.97E-09	0.00E+00	0.00E+00
Carbon dioxide	9.14E-04	7.96E-04	8.31E-05	3.42E-05
Carbon monoxide	7.63E-06	6.87E-06	7.01E-07	6.13E-08
Nitrogen oxides	1.62E-06	1.40E-06	1.39E-07	7.77E-08
Nitrous oxide (laughing gas)	1.81E-08	1.38E-08	4.32E-09	0.00E+00
Sulfur dioxide	4.75E-06	4.40E-06	1.89E-07	1.58E-07
Sulfur hexafluoride	8.08E-14	8.08E-14	0.00E+00	0.00E+00
Methane	1.37E-06	1.31E-06	6.30E-08	0.00E+00
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	4.39E-08	3.15E-08	1.24E-08	0.00E+00
Particulate Matter, unspecified	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dust (unspecified)	1.42E-06	1.35E-06	1.99E-08	4.51E-08

The total number of railcars, 100, was defined by the Baseline Report (NETL, 2010), The weight for one empty railcar was estimated based on the average of two different railcars based on manufacturer information; the FreightCar America's BethGon II railcar and Trinity Rail's 4,402 cubic foot aluminum rotary Gondola railcar (FreightCar America, 2008; Trinity Rail, 2008). The BethGon II weighed 18,915 kg (41,700lbs), while the Gondola weighs 19,051kg (42,000 lbs) (FreightCar America, 2008; Trinity Rail, 2008). This translates to an average empty railcar weight of 18,983 kg (41,850 lbs). According to the Baseline Report, one railcar has the capacity to carry 100 tons or 90,718 kg (200,000 lbs) of coal (NETL, 2010). The total weight of the one loaded railcar loaded is equal to 109,701 kg (241,850 lbs) or 110 tonnes (121 tons).

To calculate the number of locomotives needed to pull 100 loaded railcars, the total horsepower (hp) needed to move all the railcars was determined by inputting the total loaded weight of 100 cars into a correlation equation developed for the California Energy Commission (TIAX LLC, 2007). The equation is shown in **Figure A-10**. It was calculated that in order to pull 100 railcars, weighing a total 10,970 tonnes (12,093 tons), 21,310 of horsepower was needed. One locomotive has a horsepower of 4,400 (General Electric, 2008); therefore in order to match the horsepower needed it was calculated that 5 locomotives would be needed to pull 100 loaded railcars.

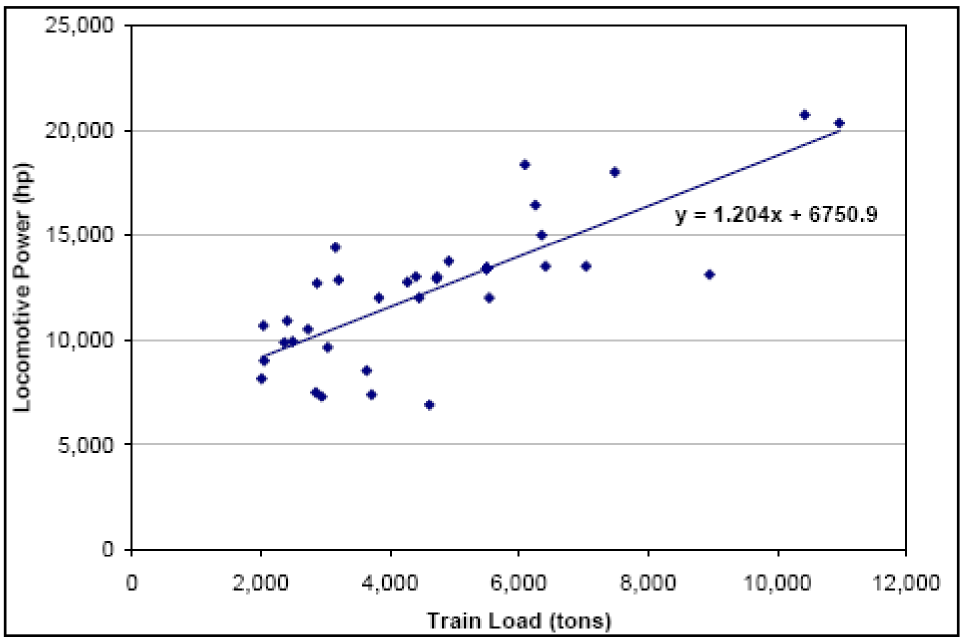

Figure A-10: Train Load and Locomotive Power Relationship (TIAX LLC, 2007)

A locomotive is estimated to have a useful life of approximately 20 years depending upon maintenance and operation (GE Transportation, 2009). The railcars are estimated to have a lifetime of 30 years (Department of Transport [UK], 2009); because this is the same as the study lifetime no railcar replacements will be needed. However, because locomotives have a lifetime shorter than that of the plant, a replacement set will be constructed and will replace the original five locomotives 20 years into the lifetime of the plant. It was calculated that each locomotive being used will be replaced once, making it necessary to use 10 locomotives over the life of the plant. However, because the second set of locomotives will only be used for half of their overall lifetime, it was calculated that only 7.5 – equivalent locomotives will be needed over the assumed lifetime of the plant. **Table A-9** summarizes the data and calculations.

Table A-9: Railcar and Locomotives Needed over the Lifetime of the Energy Conversion Facility

Parameters	Value	Reference
Number of Railcars	100	NETL 2007
Weight of One Loaded Railcar Tonnes (Tons)	110 (121)	FreightCar America 2008 Trinity Rail 2008
Weight of 100-Cars Tonnes (Tons)	10,970 (12,093)	Calculated
Total HP Required to Pull 100 Cars	21,310	Calculated (TIAX LLC, 2007)
Locomotive Horsepower	4,400	GE Transportation 2008
Estimated Number of Locomotives[1]	5	Calculated
Locomotive Estimated Lifetime (Years)	20	GE Transportation 2009
Railcar Estimated Lifetime (Years)	30	(Department of Transport [UK], 2009)
Assumed Plant Lifetime (Years)	30	NETL 2007
Sets of Locomotives Needed Over Plant Lifetime[2]	1.5	Calculated
Sets of Railcars Needed Over Plant Lifetime[2]	1	Calculated
Total Number of Locomotives Needed[3]	7.5	Calculated
Total Number of Railcars Needed[3]	100	Calculated

[1] Rounded up to the nearest whole number.
[2] One set of locomotives is equal to the number of locomotives needed to pull the 100 railcars. In this case, it is 5 locomotives per set. One set of railcars is equal to 100 railcars.
[3] Total number needed over the lifetime of the Energy Conversion Facility.

The round-trip mine-to-plant miles is an adjustable parameter used to determine how many unit trains are necessary; this value is adjusted during the sensitivity analysis to assess the influence transport distance has on the overall LC. Data for the amount of time it takes a coal unit train to get loaded, travel to the energy conversion facility, unload, and return to the coal mine were calculated using weekly performance statistics from six major North American rail companies (BNSF Railway Company, Canadian Pacific *et al.*, 2009). Based on data for each company from the first quarter of 2008, it was determined that the average speed of coal unit trains was approximately 20 mph. Using dwell time data from the same source, it was determined that unit trains dwell for approximately 24 hours (BNSF Railway Company, Canadian Pacific *et al.*, 2009); where it was assumed that the dwell time was the amount of time the train spends being loaded or unloaded. By dividing the round-trip distance by the average speed and adding that to the loading and unloading times, the total amount of time for a single trip was calculated. For a round-trip distance of 1,170 miles, the trip time is 106.5 hours.

In order to put the construction of the locomotives and railcars on a per kg of coal basis, the total amount of coal that can be transported by a single unit train over the lifetime of the plant had to be determined. By multiplying the number of hours in 30 years (the lifetime of the plant) by the capacity of a unit train, and dividing by the number of hours in a single trip, that amount is calculated. For a 100-car, 100-ton per car capacity unit train traveling 1,170 miles, this comes out to 22,385,741,753 kg of coal.

The final step in this process is calculating the number of locomotives and railcars necessary to transport one kg of coal 1,170 miles over the lifetime of the plant. This was done by multiplying the number of locomotives (or railcars) by the locomotive (or railcar) replacement rates to get a total number of locomotives (or railcars) over the life of the plant, and dividing that value by the amount of coal transported over 30 years by a unit train. For the IGCC cases, the values are 3.24 $\times 10^{-10}$ locomotives/kg transported coal and 4.47×10^{-09} railcars/kg transported coal.

A railcar was assumed to be manufactured from steel and aluminum. Using data from Amsted Rail, it was calculated that steel accounts for approximately 35 percent of the total weight; therefore it was assumed that 65 percent was manufactured from aluminum (Amsted Rail, 2008). Lacking specific data, the locomotive was considered to be manufactured from 10 percent stainless steel and 90 percent carbon steel.

A.1.2.3 Operation Assumptions

The scope of this process covers rail transport of coal in the United States, and estimates criteria pollutant emissions, CO_2 emissions, and fugitive dust emissions on the basis of 1 kg of coal being transported along a user-defined distance (1,170 miles for the IGCC case). The calculation assumes that backhaul and fronthaul have the same energy intensity and emission profile. The diesel locomotive, which would operate from 2010 to 2040, is assumed to meet the emission standards EPA's Tier 4 emissions criteria for the duration of the 30 year period. Note that the Tier 4 emissions standards are set to become effective in 2015. Accordingly, diesel consumed by the train is assumed to be ULSD, with a sulfur content of 15 parts per million.

The energy requirement/diesel consumption factor used for the diesel locomotive was taken from US Bureau of Transportation statistics for 2008, which includes energy intensity data for railroad freight service (DOT, 2008). Emission factors were taken from EPA's Tier 4 standard for diesel locomotive engines, for NO_X, PM, VOCs, and CO (EPA, 2008b). Emission factors for CO_2, CH_4, and N_2O were taken from the national emissions inventory (EPA, 2005b). SO_2 emissions are calculated based on the sulfur content of ULSD, and assuming complete stiochiometric conversion from S to SO_2 during diesel combustion.

Fugitive coal dust emissions are based on a study of Australian coal mine transport in Queensland, Australia (Cornnell Hatch, 2008). Therein, fugitive coal dust emissions were quantified on a per metric tonne basis over distances ranging from approximately 125 to 500 km. Fugitive coal dust emissions were then normalized to a basis of kg coal dust emissions per kg-km of coal transport, and incorporated into the DS sheet calculations.

The amount of Hg released as a result of the combustion of diesel was based on information from a study examining gasoline and diesel fuel combustion in the San Francisco Bay area of California (Conaway, Mason *et al.*, 2005). An emission factor for NH_3 from the combustion of diesel from mobile sources was obtained from a report that developed emission factors for various sources of NH_3 (Battye, Battye *et al.*, 1994). The GaBi plan for train transport operation is located in **Figure A-11**, with 1 kg representing 1 kg of processed coal from the mine. **Table A-10** shows the GaBi air emission outputs due to Stage #2 operations.

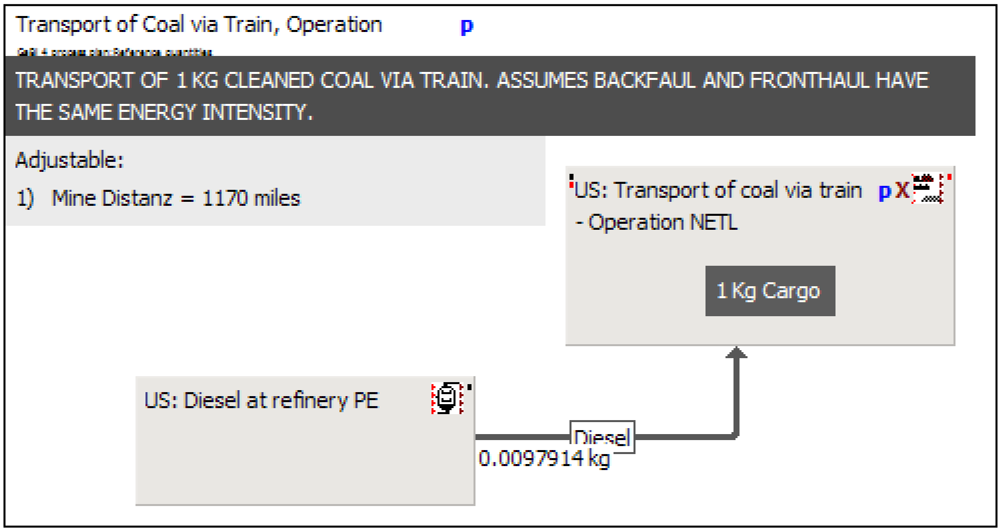

Figure A-11: GaBi Plan for the Operation of a Unit Train

Table A-10: GaBi Air Emission Outputs and Profiles for Stage #2 Operations, kg/kg Coal Delivered to the Plant

Emissions (kg/kg coal delivered)	Total	Diesel at refinery PE	Transport of Coal Via Train
Lead	1.82E-10	1.82E-10	0.00E+00
Mercury	1.70E-11	1.54E-11	1.52E-12
Ammonia	1.30E-06	2.70E-08	1.27E-06
Carbon dioxide	3.50E-02	4.03E-03	3.10E-02
Carbon monoxide	1.01E-04	5.89E-06	9.52E-05
Nitrogen oxides	9.50E-05	1.25E-05	8.25E-05
Nitrous oxide (laughing gas)	6.90E-08	6.90E-08	0.00E+00
Sulfur dioxide	1.65E-05	1.62E-05	2.92E-07
Sulfur hexafluoride	1.54E-14	1.54E-14	0.00E+00
Methane	4.44E-05	4.19E-05	2.44E-06
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	8.90E-06	1.75E-08	8.88E-06
Particulate Matter, unspecified	1.18E-04	0.00E+00	1.18E-04
Dust (unspecified)	2.39E-07	2.39E-07	0.00E+00

A.1.3 Life Cycle Stage #3, Case 1: IGCC Energy Conversion Facility without CCS

Stage #3, Case 1 includes the commissioning, construction, operation, and decommissioning of a 640-MWe net output IGCC plant without CCS; most data were taken from the Baseline Report (NETL, 2010).

A.1.3.1 GaBi Plan

Figure A-12 defines the second level GaBi plan for the IGCC case without CCS. This plan is based on a reference flow of 1 MW electricity output over the 30-year study lifetime.

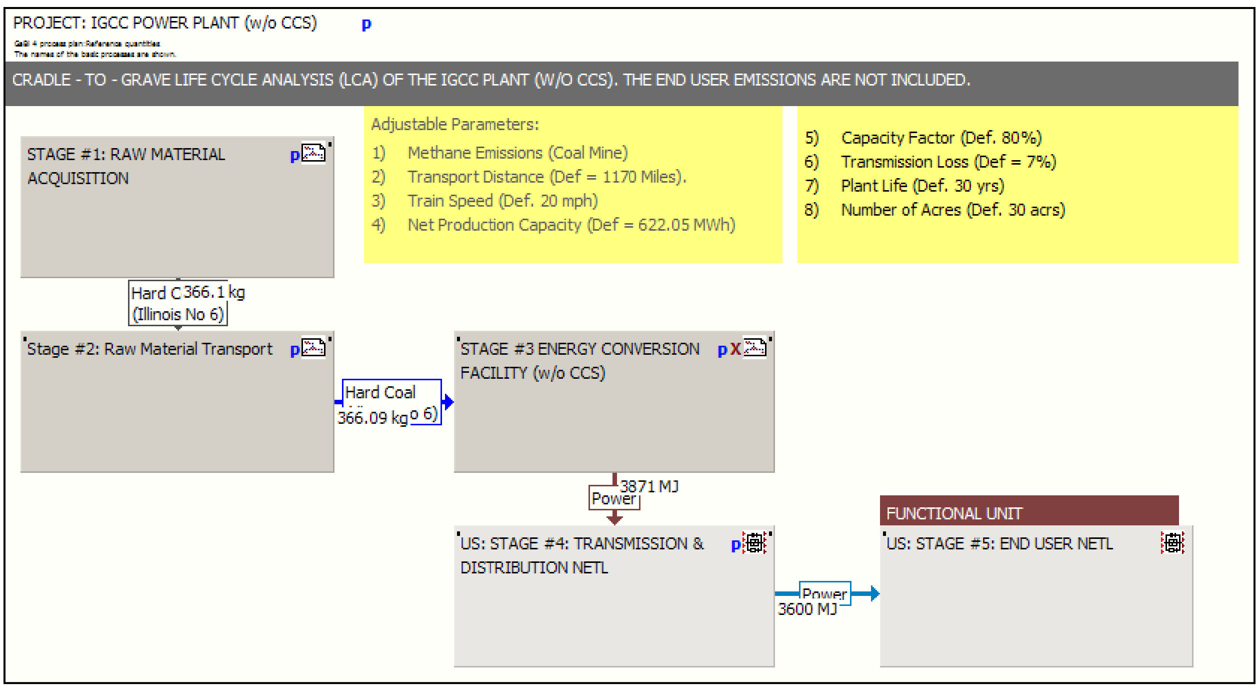

Figure A-12: GaBi Plan for IGCC Case without CCS

A.1.3.2 Commissioning, Installation, and Decommissioning Assumptions

The energy and water used and emissions associated with the installation and deinstallation of a power plant are dominated by the use of diesel fuel to power construction equipment. Data for the installation of a power plant came from the Russell City Energy Center Application for Certification to the California Energy Commission (Calpine/Bechtel, 2001). The application was for the proposed Russell Energy Center, a 14.7 acre, 600-MW NGCC plant with equipment needs (two gas turbines with heat recovery steam generators and one steam turbine) similar to those in the Baseline Report (NETL, 2010).

The application included data on diesel fuel use, water use, and criteria air pollutants associated with a 21-month installation period. The data were calculated assuming many emission control measures were implemented, including water spray for dust suppression, low sulfur fuels, preventative maintenance on construction equipment, and limited idling time (Calpine/Bechtel, 2001). It is noted as a minor data limitation that emissions are based on a plant in California, while our model is considering a plant in Illinois. Some differences are expected due to varying landscapes and regulatory requirements.

Although it was assumed that water suppression was used to control PM emissions, no data were given on the specific amount of water used during installation. This amount was calculated using a given application rate of water, and took into account several assumptions. The application stated that most of the plant fugitive dust emissions occurred in the first month or two and thus water usage was only calculated for the first two months (Calpine/Bechtel, 2001). The application also stated that the construction process would occur from 6 a.m. to 6 p.m., Monday through Saturday, for a total of 288 hours of construction per month of activity (Calpine/Bechtel, 2001). Finally, it was assumed that the application rate of 0.25 hours per application (or four applications per hour) was incorrectly reported in the source (Calpine/Bechtel, 2001); applying that amount of water would result in approximately one inch of water per day being used over the entire installation area. RDS felt that, although dust would be suppressed, such an amount of water would cause additional problems with standing water and mud. Therefore, an adjusted application rate of 0.25 applications per hour was assumed, which correlated to one application every four hours. This application rate seemed more practical, and an inverse of units as written in the original report is a realistic error.

Diesel use during installation was obtained from the Russell City Energy Center Application for Certification (Calpine/Bechtel, 2001). In Appendix 8.1-E, Table 8.1E-8 lists the total diesel use (gallons per year) for each piece of construction equipment. These amounts were summed for a total of 122,817.7 gal/yr. This value was multiplied by the length of the construction period, 21 months (or ~1.75 years), for the volume over the entire construction period. This value was then multiplied by the density of diesel (7.1 lb/gal) and converted to kilograms (American Petroleum Institute, 2004).

The amount of CO_2 released during installation of the power plant was calculated by first determining how much carbon was present in the amount of diesel used. There are 2,778 grams of carbon in one gallon of diesel (EPA, 2005a). The amount of carbon in the diesel (568,645.9 kg) was converted to CO_2 by following EPA and IPCC guidelines, which state that 99 percent of carbon in a fuel is oxidized and emitted as CO_2, and the mass of CO_2 was determined multiplying by the ratio of the molecular weights of CO_2 (44 moles/gram) and carbon (12 moles/gram) (EPA, 2005a). The total calculated mass of CO_2 released during construction was divided by the number of acres of construction that the study was based on (14.7, Calpine/Bechtel, 2001) to determine kg/acre of CO_2.

Table 8.1E-3 of the Russell City application lists the emissions, in tons/year, for five pollutants – NO_X, CO, VOC, SO_X, and PM (Calpine/Bechtel, 2001). The values for each, 22.95 tons/yr for NO_X, 63.82 tons/year for CO, 6.09 tons/year for VOC, 0.58 tons/year for SO_X, and 3.1 tons/year for PM, were multiplied by the number of years of construction (1.75) and then converted into kilograms. Finally, these values were divided by the total area of the construction site to get the amount of each emission per acre.

The emissions of four other pollutants were calculated using different sources – CH_4, N_2O, NH_3, and Hg. The emissions factors for CH_4 and N_2O were pulled from Appendix H of a DOE report, which references the EPA GHG inventory (EPA, 2008e). It was assumed that the diesel-powered construction equipment would be representative of the equipment used at the power plant. These emission factors were 0.58 g/gallon of diesel for CH_4 and 0.26 g/gallon for N_2O (EPA, 2008e). The NH_3 emission factor was obtained from a report published by the EPA documenting the development and selection of emission factors for NH_3. The emission factor for the combustion of diesel from mobile sources was given as 0.11 kg/1000 L of diesel (Battye, Battye *et al.*, 1994). The emission factor of the final pollutant, Hg, was determined by dividing the average concentration of Hg in diesel from various studies by the number of samples to get 0.1564 ng/g diesel (Conaway, Mason *et al.*, 2005).

Each of the pollutants was converted from their emission factor units into kg/acre to correspond with the other emissions. Both the CH_4 and N_2O emissions were calculated by converting first to kg/gallon of diesel, and then by multiplying by the previously-determined gallons of diesel used per acre of development. The NH_3 was also converted to kg/gallon and multiplied by the gallons of diesel used, but there was an intermediate conversion from 1000 L to gallons. Finally, the Hg was converted by changing g diesel to kg diesel, multiplying by the diesel use per acre (in kg/acre), and dividing by 10^{12} (ng/kg). These calculations gave total emissions, per acre of development, of 8.48 kg CH_4, 3.80 kg N_2O, 6.09 kg NH_3, and 7.36 x 10^{-06} kg Hg.

The total amount of water and diesel used and the emissions released includes decommissioning of the power plant site. It was assumed that the decommissioning use and emissions were 10 percent of the total commissioning use and emissions (Odeh and Cockerill, 2008). The diesel use, water use, and emissions were all multiplied by 10 percent, and this value was added onto the total values previously calculated on a per acre of installation basis.

Figure A-13 represents the GaBi plan for power plant installation/deinstallation. This is the same for all cases within this study. **Table A-11** gives the GaBi emission outputs and profiles associated with this process.

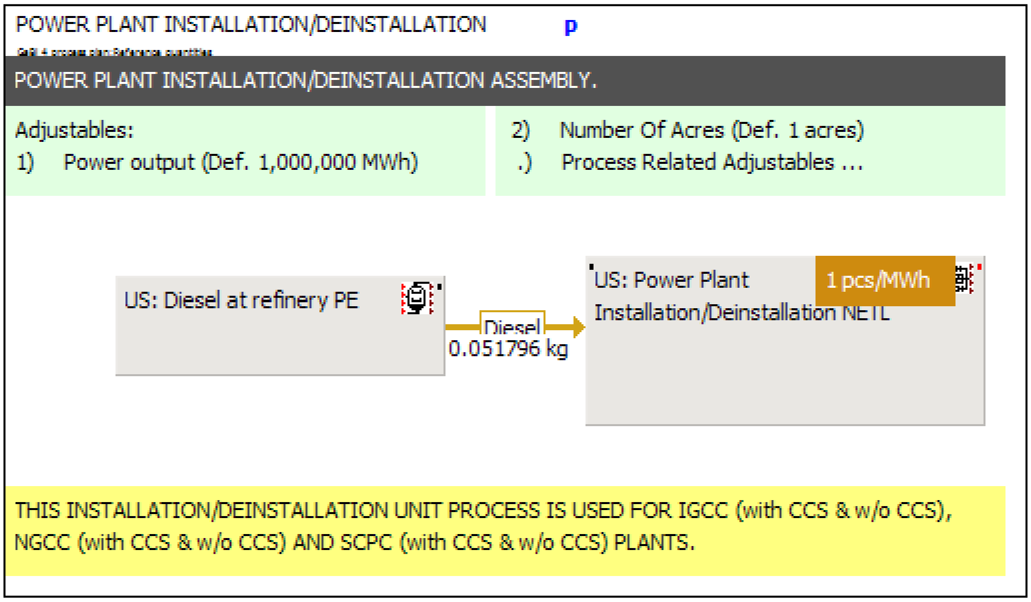

Figure A-13: GaBi Plan for Power Plant Installation/Deinstallation

Table A-11: GaBi Air Emission Outputs and Profiles for Power Plant Installation/Deinstallation, kg/MWh Plant Output

Emissions (kg/MWh plant output)	Total	Diesel at refinery PE	Power Plant Installation/Deinstallation
Lead	2.56E-10	2.56E-10	0.00E+00
Mercury	2.38E-11	2.17E-11	2.15E-12
Ammonia	1.81E-06	3.78E-08	1.78E-06
Carbon dioxide	4.87E-02	5.66E-03	4.30E-02
Carbon monoxide	2.02E-03	8.26E-06	2.01E-03
Nitrogen oxides	7.41E-04	1.76E-05	7.23E-04
Nitrous oxide (laughing gas)	1.21E-06	9.69E-08	1.11E-06
Sulfur dioxide	4.10E-05	2.27E-05	1.83E-05
Sulfur hexafluoride	2.16E-14	2.16E-14	0.00E+00
Methane	6.13E-05	5.88E-05	2.47E-06
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	1.92E-04	2.45E-08	1.92E-04
Particulate Matter, unspecified	9.77E-05	0.00E+00	9.77E-05
Dust (unspecified)	3.35E-07	3.35E-07	0.00E+00

A.1.3.3 Construction Assumptions

This process encompasses the material inputs necessary for the construction of an IGCC power plant without carbon capture and sequestration. The inputs and outputs are expressed in terms of units per megawatt-hour of produced power. The data includes materials from three main components of an energy conversion facility – the power plant itself, the trunkline and switchyard to transmit electricity from the plant to the power grid, and a rail spur to get the fuel (coal) from the main rail line to the plant.

Data for the construction of the power plant were taken from five studies, each of which listed the amounts of between three and five major materials for construction. These five studies included data on seven operating, proposed, or hypothetical IGCC plants. The materials for the construction of the plant, according to the various studies, were concrete, steel, steel pipes, iron, and aluminum (Spath, Mann *et al.*, 1999; CononcoPhillips, 2005; ELCOGAS, 2000; Fiaschi and Lombardi, 2002). The amounts of each construction material given in the studies was divided by the net output of the plant in the study to put them on a per MW produced basis. Each material that was listed in more than one study or for more than a single plant was averaged and the value was converted to kilograms, to give construction materials in kg/MW.

The data for the rail spur was taken from information from the American Railway Engineering Association (ICRR, 2007). The weight of rail, in lb/yd, was converted to kg/mile and then multiplied by 25, the assumed length of the rail spur from the main line to the power plant. The rail was assumed to be constructed of cold-rolled steel.

There are four components for the switchyard and trunkline – the transmission towers, the foundation for the towers, air break switches, and circuit breakers. The necessary materials for each component were calculated individually and then summed across the entire switchyard and trunkline.

The towers are assumed to be lattice steel towers, each weighing approximately 8.75 tons (Brune, 2008). Each leg (four on each tower) of a tower is supported by a cylindrical concrete foundation 3.50 ft. wide and 22.50 ft. deep (Aspen Environmental Group, 2008). The volume of each foundation was multiplied by four for the volume of concrete for one tower, and then multiplied by the density of concrete (Portland Cement Association, 2008) to get the total weight of concrete for a single tower. To determine the number of towers in the trunkline, it was assumed that it was 50 miles long (Skone, 2008) and that the towers were spaced approximately every 900 ft. (CapX 2020, 2007). This results in 293 towers over the 50 miles. Finally, to calculate the amount of concrete and steel in the trunkline towers, the weight of each for a single tower was multiplied by the total number of towers.

For the conductors, it was assumed that there was a single three-phase conductor running the length of the trunkline. There was no allowance for sag in the calculation of conductor length, and there was no consideration for electrical losses. The conductors are aluminum conductors, aluminum-clad steel reinforced (ACSR/AW), and are sized to carry the net plant output, based on cable ampacity. The ampacity of the conductors, based on an output of 640.25 MW, a voltage of 345,000, and a power factor of 90 percent is 1,190 amps. The smallest size conductor that can carry 1,190 amps is 1272 MCM (Phelps Dodge, 2005). For this size conductor, the aluminum and steel components were converted from lb/1000 ft. to kg/mile, and then multiplied by the assumed trunkline distance of 50 miles to get a total weight of aluminum and steel for the conductors.

The next component was the switchyard air break switch. It was assumed that there will be eight total air break switches – two for each SF_6 circuit breaker. Once again, the conductors coming through the switchyard air break switches are three phase and there are assumed to be three sets of two 220 kV rated insulators to make an insulator rated for 345 kV. The weight of a single 220 kV insulator was gathered from vendor data (Keidy Electro-Mechanical Company, 2008). As stated previously, there are three sets of two insulator assemblies per phase, and taking that total times the number of phases gives the total weight of insulators for one air break switch.

To calculate the amount of steel in an air break switch, it was assumed that all components except for the insulators were constructed of steel. To get the weight of one air break switch, the weight of a switch for one phase (General Switchgear & Controls, 2008) was multiplied by the number of phases. The weight of the insulators was subtracted from the total weight of one air break switch to get a total estimated amount of steel for a single switch.

The last component of the air break switches is the concrete foundation. It was assumed that the foundation of one phase of a switch would be roughly the same size as the foundation of one leg of the conductor towers. The foundations are cylindrical, and the volume was multiplied by the density of concrete to determine the total weight for all three phases of one air break switch. One final step for the air break switches was to multiply each material (steel, concrete, and insulators) by the total number of switches for the switchyard, and then convert everything to kilograms.

The final component of the switchyard and trunkline are the SF_6 circuit breakers. There are a total of four, three-phase SF_6 breakers at the plant. There are two insulator assemblies per phase, and each assembly has two 220-kV insulators. The weights of a single circuit breaker and the amount of SF_6 in each breaker were taken from vendor specifications (HVB AE Power Systems, 2003). Again, the weight of insulators in a breaker was calculated by taking the weight of one insulator (Keidy Electro-Mechanical Company, 2008) and multiplying by the number of insulators in an assembly, the number of assemblies per phase, and the number of phases for one breaker. The amount of steel in one circuit breaker was determined by subtracting the weight of SF_6 and the weight of the insulator assemblies from the total weight of a single circuit breaker.

The concrete foundation assumptions and calculations are identical to those of the air break switches. The final step for the circuit breakers was to multiply the weight of each material (steel, concrete, SF_6, and insulators) by the total number of breakers in the switchyard and converting to kilograms.

The weights of all the construction materials for the switchyard and trunkline were summed – cold-rolled steel for the towers, conductors, air break switches, and SF_6 circuit breakers; concrete for the foundation of the tower, switches, and breakers, aluminum for the conductors, insulators for the switches and breakers, and SF_6 for the circuit breakers.

Finally, the construction materials for each plant site component (power plant, rail spur, switchyard and trunkline) were divided by the total megawatts of electricity produced during the lifetime of the plant. This put each major component on a kg/MWh produced basis. Lastly, materials present in more than one of the plant site components were added together to give a total for the process. **Figure A-14** represents the GaBi plan and **Table A-12** shows the air emissions and material profiles used for IGCC plant construction without CCS.

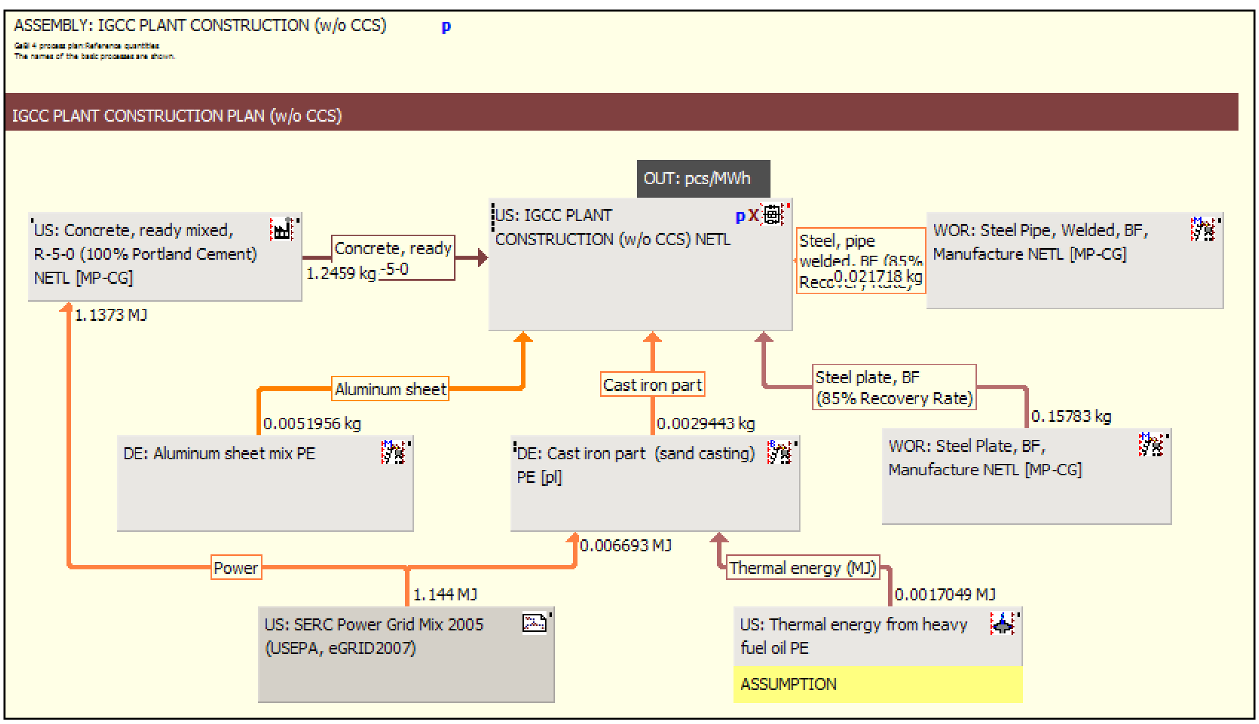

Figure A-14: GaBi Plan for IGCC Plant Construction without CCS

Table A-12: GaBi Air Emission Outputs and Profiles used for IGCC Plant Construction without CCS, kg/MWh Plant Output

Emissions (kg/MWh Plant Output)	Total	SERC Power Grid Mix 2005 (USEPA, eGRID2007)	Aluminum sheet mix PE	Cast iron part (sand casting) PE [pl]	Concrete, Ready Mixed, R-5-0 (100% Portland Cement)	Thermal energy from heavy fuel oil	Steel Pipe, Welded, BF, Manufacture	Steel Plate, BF, Manufacture
Lead	5.29E-07	1.30E-08	8.55E-09	2.07E-10	0.00E+00	2.98E-11	8.40E-08	4.23E-07
Mercury	3.31E-08	3.67E-09	5.99E-10	8.03E-12	0.00E+00	1.38E-13	2.22E-09	2.66E-08
Ammonia	1.55E-06	1.25E-06	2.85E-07	8.08E-09	0.00E+00	1.07E-09	0.00E+00	0.00E+00
Carbon dioxide	7.71E-01	2.61E-01	6.45E-02	4.17E-03	2.00E-01	1.83E-04	2.76E-02	2.14E-01
Carbon monoxide	2.97E-03	1.08E-04	5.95E-04	5.28E-06	2.58E-04	6.74E-08	2.04E-04	1.80E-03
Nitrogen oxides	1.61E-03	5.06E-04	8.81E-05	3.27E-06	6.11E-04	2.09E-07	4.50E-05	3.58E-04
Nitrous oxide (laughing gas)	1.76E-05	3.46E-06	1.40E-06	5.99E-08	0.00E+00	1.60E-09	1.54E-06	1.11E-05
Sulfur dioxide	2.76E-03	1.48E-03	2.42E-04	2.34E-06	4.65E-04	7.74E-07	7.83E-05	4.86E-04
Sulfur hexafluoride	9.96E-12	1.78E-12	8.17E-12	1.42E-14	0.00E+00	7.88E-17	0.00E+00	0.00E+00
Methane	5.83E-04	2.86E-04	1.02E-04	3.33E-06	0.00E+00	1.89E-07	2.92E-05	1.62E-04
Methane (biotic)	9.13E-06	0.00E+00	0.00E+00	0.00E+00	9.13E-06	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	6.08E-05	3.64E-08	2.76E-06	1.11E-10	2.25E-05	7.61E-11	3.72E-06	3.18E-05
Particulate Matter, unspecified	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dust (unspecified)	8.32E-04	2.81E-05	1.17E-04	6.83E-06	5.96E-04	3.42E-09	3.24E-05	5.12E-05

A.1.3.4 Operation Assumptions

All primary operations of the IGCC plant without CCS plant are included in this unit process, using inputs of coal, air, and process water to produce electricity. Emissions output from operation of the plant also include those from an auxiliary boiler during 50 percent of plant downtime, and leakage of SF_6 from circuit breakers at the 345-kV switchyards at either end of the trunkline.

The IGCC plant without CCS was modeled using the Baseline Report results for Case 1, a single stage, entrained-flow, slurry fed gasifier using Illinois #6 coal and producing a net output of 640 MWe (NETL, 2010). An 80 percent capacity factor is given, making the calculated net output 512.2 MWh (NETL, 2010). **Figure A-15** and **Table A-13** show the GaBi plan and profile emissions for this process.

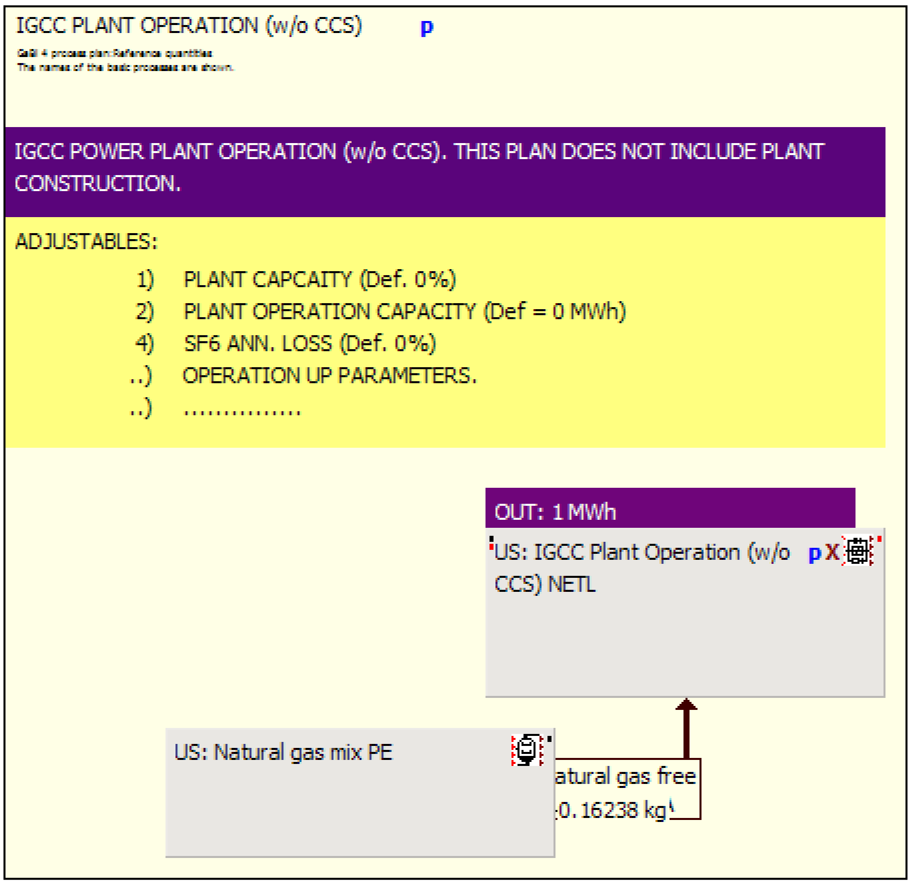

Figure A-15: GaBi Plant for IGCC Plant Operation without CCS

Table A-13: GaBi Air Emission Outputs and Profiles for IGCC Plant Operations without CCS, kg/MWh Plant Output

Emissions (kg/MWh Plant Output)	Total	IGCC Plant Operation (w/o CCS)	US: Natural gas mix PE
Lead	1.33E-05	1.33E-05	5.49E-09
Mercury	2.53E-06	2.53E-06	5.17E-10
Ammonia	2.39E-07	0.00E+00	2.39E-07
Carbon dioxide	9.04E+02	9.04E+02	7.44E-02
Carbon monoxide	4.78E-04	3.75E-04	1.03E-04
Nitrogen oxides	2.72E-01	2.72E-01	2.24E-04
Nitrous oxide (laughing gas)	4.32E-06	2.86E-06	1.46E-06
Sulfur dioxide	6.21E-03	5.90E-03	3.09E-04
Sulfur hexafluoride	3.32E-07	3.32E-07	6.28E-13
Methane	8.94E-04	1.03E-05	8.84E-04
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	2.52E-05	2.46E-05	5.82E-07
Particulate Matter, unspecified	3.29E-02	3.29E-02	0.00E+00
Dust (unspecified)	6.39E-06	0.00E+00	6.39E-06

Air Emissions

Auxiliary Boiler Operation

During IGCC plant non-operation, the Baseline Report specifies that a shop fabricated, 40,000 lb/hr, 400 psi water tube auxiliary boiler is used to replace the primary system. It is assumed that the auxiliary boiler is operated for 50 percent of the downtime such that operation time for the boiler is calculated to be 10 percent of one year.

The only mention of the auxiliary boiler in the Baseline Report is that it can use either oil or gas; no fuel use amounts or emissions associated with the auxiliary boiler operation are included. Therefore, natural gas was assumed as the fuel used (versus fuel oil), and consumption of the auxiliary boiler is estimated to be 53,000 standard ft^3/hr based upon highest fuel consumption claims for two similarly sized boilers in the sited brochures (Wabash Power Equipment Company, 2009). Using 23.8 ft3/lb as the specific volume of natural gas, auxiliary boiler natural gas consumption is calculated to be 0.1578 kg/MWh.

A controlled burn emissions profile is added for natural gas combustion in a large-walled boiler from AP 42, under the assumption that a low-NO_X burner is used (EPA, 1998). T he boiler emits NO_X, CO, CO_2, N_2O, PM, SO_2, CH_4, VOC_X, and lead. Hg emissions from natural gas were assumed to be negligible as reliable data were not found and Hg is not a typical contaminant in natural gas supplies. Emission rates for each pollutant or gas is included in **Table A-14**. These values were converted to kg/MWh of net output. No NH_3 emission values for the auxiliary boiler were identified.

Table A-14: Air Releases from Auxiliary Boiler

Pollutant	lb/ 10^6 SCF	kg/MWh
NO_x (controlled)	140	5.26×10^{-04}
CO	84	3.15×10^{-04}
CO_2	120000	0.45
N_2O (controlled)	0.64	2.4×10^{-06}
PM (total)	7.6	2.85×10^{-05}
SO_2	0.6	2.25×10^{-06}
CH_4	2.3	8.64×10^{-06}
VOC	5.5	2.07×10^{-05}
Hg	N/A	N/A
Lead	0.0005	1.88×10^{-09}

Primary IGCC Plant Operation

The IGCC plant without CCS consumes 466,901 lb/hr of coal as specified in the Baseline Report, which is equivalent to an average of 340.46 kg/MWh net electricity output. On the basis of these flows, air releases from plant operation are given in the Baseline Report Case 1, Exhibit ES-2 (NETL, 2010). These air releases include CO_2, Hg, NO_X, PM, and SO_2 as shown in **Table A-15.**

Table A-15: Air Releases from IGCC Plant without CCS

Emissions	lb/hr	kg/MWh
CO_2	1072080	650
Hg	0.003	1.89×10^{-06}
NO_X	322	0.195
PM	39	0.023
SO_2	7	.0041

Lead and NH_3 emissions data are not available in the Baseline Report. In order to generate an estimate for lead emissions, data were incorporated from a prior Environmental Assessment of IGCC Power Systems (EPA, 2008a; EIA, 2002). Airborne lead emissions for this study is reported as 2.9×10^{-12} lb/BTU, equivalent to 2.53×10^{-05} lb/MWh using the net plant HHV heat rate reported in Exhibit ES-2 of the Baseline Report. No NH_3 air emissions are produced by the Bituminous Baseline Aspen models. In addition, no NH_3 air emissions are reported by Tampa Electric Polk Power Station, a similar operating IGCC facility (EPA, 2007a; DOE, 2000). As a result, it is assumed that there are no NH_3 air emissions for the IGCC facility.

Circuit Breaker SF_6 Leakage

Once electricity is produced in the IGCC plant, circuit breakers are used for safety during electricity transmission. It was assumed that 4 circuit breakers would be needed to operate the IGCC plant; 3 at the output of each generator (2 CTG and 1 ST) and one at the end of the switchyard. It is common practice to use SF_6 gas in the breakers, which is a GHG with a high global warming potential. The amount of SF_6 used in each circuit breaker is given in the literature as 690 lbs; therefore the IGCC plant requires 1251.92 kg of SF_6 (HVB AE Power Systems, 2003). Although estimates vary, the national electrical manufacturers association states that the management guidelines for leakage of SF_6 from circuit breakers are 0.1 percent/year (Blackman and Averyt, 2006). This calculates to a leakage rate of 2.79×10^{-7} kg/MWh net output. This leakage rate is noted as a data limitation.

Water Withdrawal and Emissions

System requirements for water input to the IGCC plant without CCS, are given by Case 1, Exhibit 3-21 of the Baseline Report and are shown in **Table A-16**. This information sets a total water input rate 17.9 m^3/min, or 1.857 m^3/MWh of electricity delivered. Because the Baseline Report also states a 1:1 ratio of water input from municipal and groundwater supplies, the total input water to the plant from each of the two sources is calculated to be 8.95 m^3/min and 0.928 m^3/MWh.

Table A-16: Water Withdrawal for Case 1 from the Baseline Report

Water Withdrawal	Water Demand m^3/min (gpm)	Internal Recycle m^3/min (gpm)	Raw Water Makeup m^3/min (gpm)
Slurry	1.45 (384)	1.5 (384)	0
Slag Handling	0.5 (133)	0.5 (133)	0
Quench /Scrubber	2.7 (726)	0.90 (237)	1.9 (489)
Boiler Feed Water (BFW) Makeup	0.2 (54)	0	0.2 (54)
Cooling Tower Makeup	16.4 (4,321)	0.49 (129)	15.9 (4,192)
Total	21.3 (5,618)	3.34 (883)	17.9 (4,735)

Within these systems the Baseline report does not differentiate between water use (wastewater discharged to sewer) and consumption (evaporated water).

Therefore a second NETL study was used to determine the fractions of water discharged and evaporated (consumed) by the system (NETL, 2007b). The NETL study included an assessment of an IGCC plant consisting of two CTGs and a single STG, sized to 630 MWe of capacity, and located in Greenfield, Illinois (NETL, 2007b). The plant withdrew 404,754 lbs/h of coal. The overall water balance incorporated from the NETL study into the current IGCC plant is shown in Table 4.

Table A-17: IGCC Overall Water Balance

Water In/Location	Flow (gpm)	Water Out/Location	Flow (gpm)
Moisture in Coal	48.5	Water Lost in Gasification Shift	158
Syngas Combustion of H_2 in GT	493.1	Ash Handling Blowdown	81.1
Combustion Air for GT	77.5	Water with Slag	32
Raw Water	3,824	Water Loss in COS Hydrolysis	0.5
Moisture in Air to ASU	21	GT Flue Gas	912.6
		Water Treatment Effluent	22.2
		Cooling Tower Blowdown	808.8
		Cooling Tower Evaporation	2428
		Moisture in ASU Vent	21
TOTAL Water In	4,464	TOTAL Water Out	4,464

Table A-18 sums the water loss attributed to each system within the IGCC power plant without CCS. Of these losses, all except water treatment effluent and cooling tower blowdown are consumed through evaporation. Evaporative losses were calculated to be 81 percent of the total water input. Translating this consumption rate to the Baseline Report water input, 1.159 m^3 of water is consumed per MWh of electricity delivered. Water treatment effluent and cooling tower blowdown are discharged in liquid form and total 19 percent of the water input. Translating this discharge rate to the Baseline report water input yields a total wastewater discharge rate of 0.266 m^3/MWh.

Table A-18: IGCC Water Loss by Function

Function	gpm	Gal/MWh Electricity
Gasification Losses		
Water Lost in Gasification Shift	158	18.2
Ash Handling Blowdown	81.1	9.3
Water with Slag	32	3.7
Water loss in COS Hydrolysis	0.5	0.1
Water Treatment Effluent	22.2	2.5
Flue Gas Loss		
GT Flue Gas	912.6	104.8
Cooling Water Losses		
Cooling Tower Blowdown	808.8	92.9
Cooling Tower Evaporation	2,428	278.9
Total	4,443	510

It is important to note that the cooling water demand in the Baseline Report is based on an IGCC power plant located in the Midwestern United States; the IGCC plant in this study is assumed to be in Mississippi. The differences in elevation and ambient conditions between the two locations would result in differences in cooling water needs. This is noted as a data limitation in this study as no changes were made to the Baseline Report water data to account for the difference in location.

A.1.4 Life Cycle Stage #3, Case 2: IGCC Energy Conversion Facility with CCS

Stage #3, Case 2 includes the commissioning, construction, operation, and decommissioning of a 556-MWe net output IGCC plant with CCS; as with the operation of the IGCC plant without CCS most data were taken directly from the Baseline Report.

A.1.4.1 GaBi Plan

Figure A-16 defines the second level GaBi plan for the IGCC case with CCS. This plan is based on a reference flow of 1 MW electricity output. The addition of the pipeline third level plan is the main differences between Stage #3 in the two cases. Assumptions on the commissioning/decommissioning, construction, and operation of the pipeline are included in the following sections.

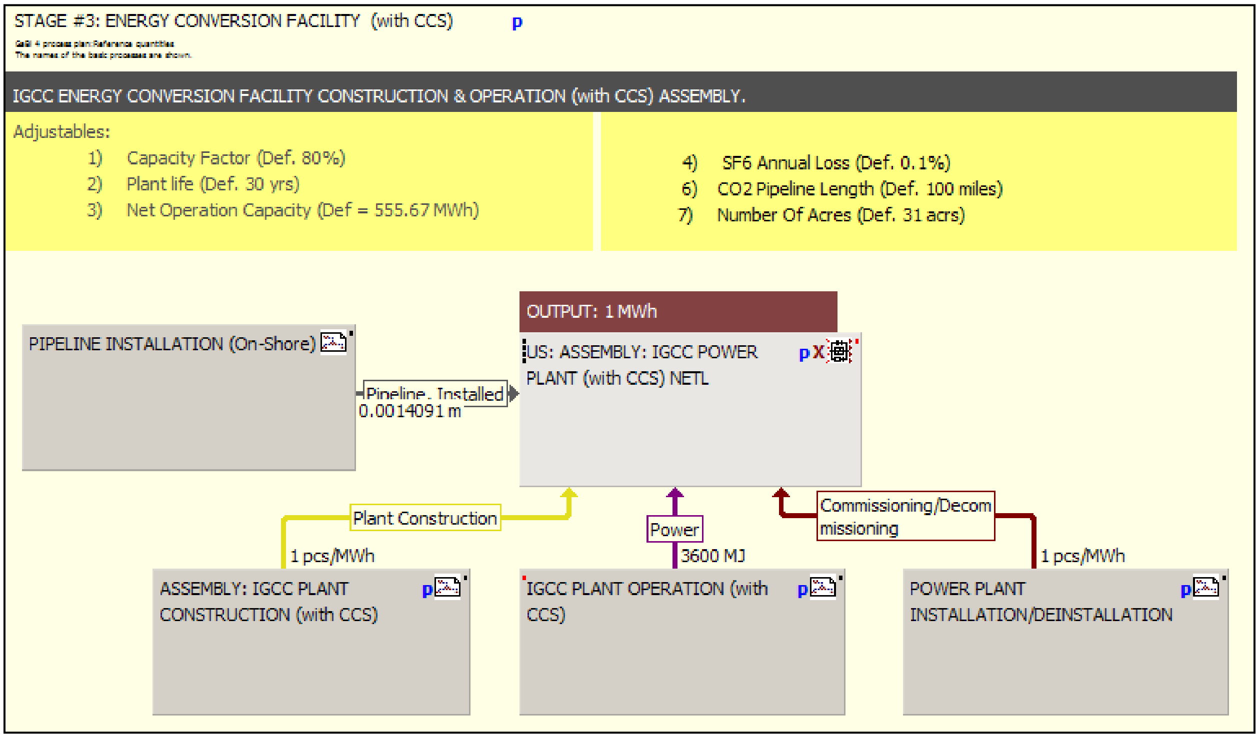

Figure A-16: GaBi Plan for Stage #3, Case 2: IGCC with CCS

A.1.4.2 Commissioning, Installation, and Decommissioning Assumptions

There are no case-specific power plant installation/deinstallation parameters within this study; **Section A.1.3.2** and **Figure A-13** represent both cases. However, the CO_2 pipeline is only used for the case with CCS and is therefore discussed here.

Emissions consistent with underground pipeline laying/construction include heavy construction equipment exhaust emissions, emissions from transport of pipes and associated materials (200 miles round-trip), and fugitive dust. PM, NO_X, SO_X, CO, and VOC emissions were estimated for pipeline installation based on the installation of a natural gas pipeline (SMUD, 2001). Emissions were placed on a per-mile-installed basis. Diesel consumption was also estimated from the aforementioned report.

The emissions of four other pollutants – CH_4, N_2O, NH_3, and Hg – were calculated using different sources in conjunction with the estimated diesel consumption (SMUD 2001). The emissions factors for CH_4 and N_2O were pulled from Appendix H of a report from DOE that cited the EPA GHG emission inventory (EPA, 2008e). It was assumed that the diesel-powered construction equipment would be representative of the diesel-powered construction equipment. These emission factors were 0.58 g/gallon of diesel for CH_4 and 0.26 g/gallon for N_2O. The NH_3 emission factor was obtained from a report published by the EPA documenting the development and selection of emission factors for NH_3. The emission factor for the combustion of diesel from mobile sources was given as 0.11 kg/1000 L of diesel (Battye, Battye *et al.*, 1994). The emission factor of the final pollutant, Hg, was determined by dividing the average concentration of Hg in diesel from various studies by the number of samples to get 0.1564 ng/g diesel (Conaway, Mason *et al.*, 2005).

Water usage for hydrotesting pipeline is ignored because water is assumed returned to source after use. Deinstallation emissions are assumed to be 10 percent of installation emissions, as consistent with the rest of the study assumptions for decommissioning. **Table A-19** shows the GaBi air emissions, including diesel used, during pipeline installation.

Table A-19: GaBi Air Emission Outputs for CO_2 Pipeline Installation/Deinstallation

Emissions (kg/MWh)	Total	US: Diesel at refinery PE	Pipeline Installation/Deinstallation
Lead	3.03E-10	3.03E-10	0.00E+00
Mercury	2.82E-11	2.56E-11	2.54E-12
Ammonia	2.15E-06	4.47E-08	2.10E-06
Carbon dioxide	5.76E-02	6.69E-03	5.09E-02
Carbon monoxide	2.39E-03	9.77E-06	2.38E-03
Nitrogen oxides	8.76E-04	2.08E-05	8.56E-04
Nitrous oxide (laughing gas)	1.43E-06	1.15E-07	1.31E-06
Sulfur dioxide	4.85E-05	2.69E-05	2.16E-05
Sulfur hexafluoride	2.55E-14	2.55E-14	0.00E+00
Methane	7.25E-05	6.96E-05	2.93E-06
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	2.27E-04	2.90E-08	2.27E-04
Particulate Matter, unspecified	1.16E-04	0.00E+00	1.16E-04
Dust (unspecified)	3.96E-07	3.96E-07	0.00E+00

A.1.4.3 Construction Assumptions

This process encompasses the material inputs necessary for the construction of an IGCC power plant with carbon capture and sequestration. The inputs and outputs are expressed in terms of units per megawatt-hour of produced power. The data includes materials from three main components of an energy conversion facility – the power plant itself with a pipeline to the sequestration facility, the trunkline and switchyard to transmit electricity from the plant to the power grid, and a rail spur to get the fuel (coal) from the main rail line to the plant. Most of the information described here was previously described for the without CCS case, but is repeated for completeness.

This process encompasses the material inputs necessary for the construction of an IGCC power plant without carbon capture and sequestration. The inputs and outputs are expressed in terms of units per megawatt-hour of produced power. The data includes materials from three main components of an energy conversion facility – the power plant itself, the trunkline and switchyard to transmit electricity from the plant to the power grid, and a rail spur to get the fuel (coal) from the main rail line to the plant.

Data for the construction of the power plant were taken from five studies, each of which listed the amounts of between three and five major materials for construction. These five studies included data on seven operating, proposed, or hypothetical IGCC plants. The materials for the construction of the plant, according to the various studies, were concrete, steel, steel pipes, iron, and aluminum (Spath, Mann *et al.*, 1999; CononcoPhillips, 2005; ELCOGAS, 2000; Fiaschi and Lombardi, 2002). The amounts of each construction material given in the studies was divided by the net output of the plant in the study to put them on a per MW produced basis. Each material that was listed in more than one study or for more than a single plant was averaged and the value was converted to kilograms, to give construction materials in kg/MW.

The data for the rail spur was taken from information from the American Railway Engineering Association (ICRR, 2007). The weight of rail, in lb/yd, was converted to kg/mile and then multiplied by 25, the assumed length of the rail spur from the main line to the power plant. The rail was assumed to be constructed of cold-rolled steel.

There are four components for the switchyard and trunkline – the transmission towers, the foundation for the towers, air break switches, and circuit breakers. The necessary materials for each component were calculated individually and then summed across the entire switchyard and trunkline.

The towers are assumed to be lattice steel towers, each weighing approximately 8.75 tons (Brune, 2008). Each leg (four on each tower) of a tower is supported by a cylindrical concrete foundation 3.50 ft. wide and 22.50 ft. deep (Aspen Environmental Group, 2008). The volume of each foundation was multiplied by four for the volume of concrete for one tower, and then multiplied by the density of concrete (Portland Cement Association, 2008) to get the total weight of concrete for a single tower. To determine the number of towers in the trunkline, it was assumed that it was 50 miles long (Skone, 2008) and that the towers were spaced approximately every 900 ft. (CapX 2020, 2007). This results in 293 towers over the 50 miles. Finally, to calculate the amount of concrete and steel in the trunkline towers, the weight of each for a single tower was multiplied by the total number of towers.

For the conductors, it was assumed that there was a single three-phase conductor running the length of the trunkline. There was no allowance for sag in the calculation of conductor length, and there was no consideration for electrical losses. The conductors are aluminum conductors, aluminum-clad steel reinforced (ACSR/AW), and are sized to carry the net plant output, based on cable ampacity. The ampacity of the conductors, based on an output of 640.25 MW, a voltage of 345,000, and a power factor of 90 percent is 1,190 amps. The smallest size conductor that can carry 1,190 amps is 1272 MCM (Phelps Dodge, 2005). For this size conductor, the aluminum and steel components were converted from lb/1000 ft. to kg/mile, and then multiplied by the assumed trunkline distance of 50 miles to get a total weight of aluminum and steel for the conductors.

The next component was the switchyard air break switch. It was assumed that there will be eight total air break switches – two for each SF_6 circuit breaker. Once again, the conductors coming through the switchyard air break switches are three phase and there are assumed to be three sets of two 220-kV rated insulators to make an insulator rated for 345 kV. The weight of a single

220-kV insulator was gathered from vendor data (Keidy Electro-Mechanical Company, 2008). As stated previously, there are three sets of two insulator assemblies per phase, and taking that total times the number of phases gives the total weight of insulators for one air break switch.

To calculate the amount of steel in an air break switch, it was assumed that all components except for the insulators were constructed of steel. To get the weight of one air break switch, the weight of a switch for one phase (General Switchgear & Controls, 2008) was multiplied by the number of phases. The weight of the insulators was subtracted from the total weight of one air break switch to get a total estimated amount of steel for a single switch.

The last component of the air break switches is the concrete foundation. It was assumed that the foundation of one phase of a switch would be roughly the same size as the foundation of one leg of the conductor towers. The foundations are cylindrical, and the volume was multiplied by the density of concrete to determine the total weight for all three phases of one air break switch. One final step for the air break switches was to multiply each material (steel, concrete, and insulators) by the total number of switches for the switchyard, and then convert everything to kilograms.

The final component of the switchyard and trunkline are the SF_6 circuit breakers. There are a total of four, three-phase SF_6 breakers at the plant. There are two insulator assemblies per phase, and each assembly has two 220-kV insulators. The weights of a single circuit breaker and the amount of SF_6 in each breaker were taken from vendor specifications (HVB AE Power Systems, 2003). Again, the weight of insulators in a breaker was calculated by taking the weight of one insulator (Keidy Electro-Mechanical Company, 2008) and multiplying by the number of insulators in an assembly, the number of assemblies per phase, and the number of phases for one breaker. The amount of steel in one circuit breaker was determined by subtracting the weight of SF_6 and the weight of the insulator assemblies from the total weight of a single circuit breaker.

The concrete foundation assumptions and calculations are identical to those of the air break switches. The final step for the circuit breakers was to multiply the weight of each material (steel, concrete, SF_6, and insulators) by the total number of breakers in the switchyard and converting to kilograms.

The weights of all the construction materials for the switchyard and trunkline were summed – cold-rolled steel for the towers, conductors, air break switches, and SF_6 circuit breakers; concrete for the foundation of the tower, switches, and breakers; aluminum for the conductors; insulators for the switches and breakers; and SF_6 for the circuit breakers.

The amount of pipeline for CO_2 transport and sequestration was determined as follows. The internal diameter of the pipe was calculated as described in Section 2.4.1 of the MIT report of the economics of CO_2 storage (Heddle, Herzog *et al.*, 2003) and was based on the flowrate of CO_2 to be sequestered (NETL 2007). Pipe weight was calculated using data from the Engineering Toolbox (The Engineering ToolBox, 2009). The weight included the entire pipeline from the plant to the sequestration site, and from the ground surface at the site to the injection well depth, both from the Baseline Report. An adjustable parameter was provided to account for the extra weight (a percentage) associated with pipeline valves, fittings, and sections of heavy walled pipe (for sections buried below roads, railroad tracks, river beds, etc.). The assumed value is 10 percent but is variable.

The concrete casing for the sequestration pipeline is poured in layers the get larger as the pipeline gets closer to ground surface. The 'production' casing surrounds the pipeline over its entire length. The 'surface' casing surrounds the pipeline from ground surface to a depth of approximately 750 ft., and encompasses the production casing as well as the pipeline. The 'conductor' casing surrounds the pipeline from ground surface to a depth of approximately 40 ft., and encompasses the production and surface casings as well as the pipeline (Brown, 2008). The depth of the injection well is a variable (NETL, 2010). The volume of concrete required for all three casing levels was summed and converted to a mass (Portland Cement Association, 2008).

Finally, the construction materials for each plant site component (power plant, rail spur, switchyard and trunkline, CO_2 pipeline, injection well) were divided by the total megawatts of electricity produced during the lifetime of the plant. This put each major component on a kg/MWh produced basis. Lastly, materials present in more than one of the plant site components were added together to give a total for the process. **Figure A-17** represents the GaBi plan for IGCC plant construction with CCS.

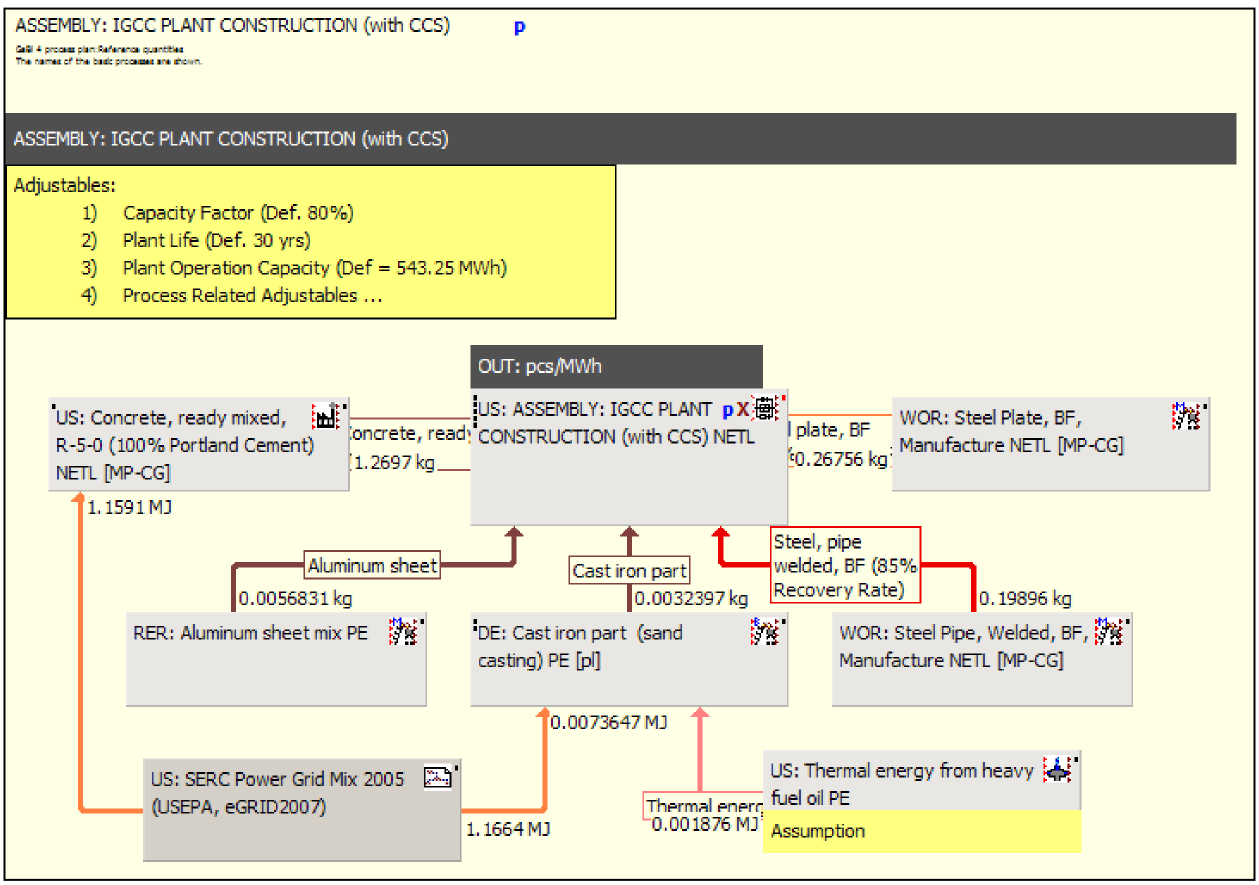

Figure A-17: GaBi Plan for IGCC Plant Construction with CCS

Table A-20 shows the air emissions associated with IGCC plant construction and life cycle emission profiles for the material and energy inputs.

Table A-20: GaBi Air Emission Outputs and Profiles for IGCC Plant Construction with CCS, kg/MWh Plant Output

Emissions (kg/MWh plant output)	Total	SERC Power Grid Mix 2005 (USEPA, eGRID2007)	Cast iron part (sand casting) PE [pl]	RER: Aluminum sheet mix PE	Concrete, Ready Mixed, R-5-0	Thermal energy from heavy fuel oil	WOR: Steel Pipe, Welded, BF, Manufacture	Steel Plate, BF, Manufacture
Lead	1.52E-06	1.33E-08	2.28E-10	1.22E-08	0.00E+00	3.27E-11	7.85E-07	7.14E-07
Mercury	7.03E-08	3.74E-09	8.84E-12	9.90E-10	0.00E+00	1.52E-13	2.08E-08	4.48E-08
Ammonia	1.57E-06	1.28E-06	8.89E-09	2.84E-07	0.00E+00	1.17E-09	0.00E+00	0.00E+00
Carbon dioxide	1.17E+00	2.66E-01	4.59E-03	7.61E-02	2.04E-01	2.02E-04	2.58E-01	3.60E-01
Carbon monoxide	5.98E-03	1.10E-04	5.81E-06	6.56E-04	2.63E-04	7.42E-08	1.91E-03	3.04E-03
Nitrogen oxides	2.30E-03	5.15E-04	3.60E-06	1.34E-04	6.22E-04	2.30E-07	4.20E-04	6.03E-04
Nitrous oxide (laughing gas)	3.80E-05	3.53E-06	6.59E-08	1.32E-06	0.00E+00	1.77E-09	1.44E-05	1.87E-05
Sulfur dioxide	3.96E-03	1.51E-03	2.58E-06	4.21E-04	4.74E-04	8.51E-07	7.32E-04	8.20E-04
Sulfur hexafluoride	9.55E-12	1.81E-12	1.56E-14	7.72E-12	0.00E+00	8.67E-17	0.00E+00	0.00E+00
Methane	9.67E-04	2.92E-04	3.67E-06	1.25E-04	0.00E+00	2.08E-07	2.73E-04	2.73E-04
Methane (biotic)	9.30E-06	0.00E+00	0.00E+00	0.00E+00	9.30E-06	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	1.14E-04	3.71E-08	1.22E-10	3.01E-06	2.29E-05	8.37E-11	3.47E-05	5.36E-05
Particulate Matter, unspecified	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dust (unspecified)	1.16E-03	2.86E-05	7.52E-06	1.29E-04	6.07E-04	3.76E-09	3.03E-04	8.64E-05

A.1.4.4 Operation Assumptions

All primary operations of the IGCC plant with carbon capture and storage (CCS) plant are included in this unit process, using inputs of coal, air, and process water to produce electricity. Emissions output from operation of the plant also include those from an auxiliary boiler operated during 50 percent of plant downtime, leakage of SF_6 from circuit breakers at the 345-kV switchyards at either end of the trunkline, and leakage of captured CO_2 from both the transport pipeline and the sequestration site.

The IGCC plant with CCS was modeled using the Baseline Report results for Case 2, a single stage, entrained-flow, slurry fed gasifier using Illinois #6 coal and producing a net output of 556 .675MWe (NETL, 2010). An 80 percent capacity factor is given, making the calculated net output 444.54 MWh (NETL, 2010). Although some processes are the same as those discussed above for the without CCS case, they are repeated here for completeness.

Air Emissions

Auxiliary Boiler Operation

During IGCC plant non-operation, the Baseline Report specifies that a shop fabricated, 40,000 lb/hr, 400 psi water tube auxiliary boiler is used to replace the primary system. It is assumed that the auxiliary boiler is operated for 50 percent of the downtime such that operation time for the boiler is calculated to be 10 percent of one year.

The only mention of the auxiliary boiler in the Baseline Report is that it can use either oil or gas; no fuel use amounts or emissions associated with the auxiliary boiler operation are included. Therefore, natural gas was assumed as the fuel used (versus fuel oil), and consumption of the auxiliary boiler is estimated to be 53,000 standard ft^3/hr based upon highest fuel consumption claims for 2 similarly sized boilers in the sited brochures (Wabash Power Equipment Company, 2009). Using 23.8 ft3/lb as the specific volume of natural gas, auxiliary boiler natural gas consumption is calculated to be 0.1578 kg/MWh.

A controlled burn emissions profile is added for natural gas combustion in a large-walled boiler from AP 42, under the assumption that a low-NO_X burner is used (EPA, 1998). The boiler emits NO_X, CO, CO_2, N_2O, PM, SO_2, CH_4, VOC_X, and lead. Hg emissions from natural gas were assumed to be negligible as reliable data were not found and Hg is not a typical contaminant in natural gas supplies. Emission rates for each pollutant or gas is included in **Table A-21**. These values were converted to kg/MWh of net output. No NH_3 emission values for the auxiliary boiler were identified.

Table A-21: Air Releases from Auxiliary Boiler

Pollutant	lb/ 10^6 SCF	kg/MWh
NO_x (controlled)	140	5.26×10^{-04}
CO	84	3.15×10^{-04}
CO_2	120000	0.45
N_2O (controlled)	0.64	2.4×10^{-06}
PM (total)	7.6	2.85×10^{-05}
SO_2	0.6	2.25×10^{-06}
CH_4	2.3	8.64×10^{-06}
VOC	5.5	2.07×10^{-05}
Hg	N/A	N/A
Pb	0.0005	1.88×10^{-09}

Primary IGCC Plant Operation

The IGCC plant with CCS consumes 500,379 lb/hr of coal as specified in the Baseline Report, which is equivalent to an average of 408.45 kg/MWh net electricity output. On the basis of these flows, air releases from plant operation are given in the Baseline Report Case 2, Exhibit ES-2 (NETL, 2010). These air releases include CO_2, Hg, NO_X, PM, and SO_2 as shown in **Table A-22**.

Table A-22: Air Releases from IGCC Plant without CCS

Emissions	lb/hr	kg/MWh
CO_2	111816	69
Hg	0.003	2.01×10^{-06}
NO_X	276	0.171
PM	40	0.025
SO_2	12	0.0076

Lead and NH_3 emissions data are not available in the Baseline Report. In order to generate an estimate for lead emissions, data were incorporated from a prior Environmental Assessment of IGCC Power Systems (EPA, 2008a; EIA, 2002). Airborne lead emissions for this study are 2.9×10^{-12} lb/BTU, equivalent to 1.38×10^{-05} lb/MWh using the net plant HHV heat rate reported in Exhibit ES-2 of the Baseline Report. No NH_3 air emissions are produced by the Bituminous Baseline Aspen models. In addition, no NH_3 air emissions are reported by Tampa Electric Polk Power Station, a similar operating IGCC facility (EPA, 2007a; DOE, 2000) As a result, it is assumed that there are no NH_3 air emissions for the IGCC facility.

Circuit Breaker SF_6 Leakage

Once electricity is produced in the IGCC plant, circuit breakers are used for safety during electricity transmission. It was assumed that 4 circuit breakers would be needed to operate the IGCC plant; 3 at the output of each generator (2 CTG and 1 ST) and one at the end of the switchyard. It is common practice to use sulfur hexafluoride (SF_6) gas in the breakers, which is a

GHG with a high GWP. The amount of SF_6 used in each circuit breaker is given in the literature as 690 lbs; therefore the IGCC plant requires 1,251.92 kg of SF_6 (HVB AE Power Systems, 2003). Although estimates vary, the national electrical manufacturers association states that the management guidelines for leakage of SF_6 from circuit breakers are 0.1 percent/year (Blackman and Averyt, 2006). This calculates to a leakage rate of 3.215×10^{-7} kg/MWh net output. This leakage rate is noted as a data limitation.

CCS System CO_2 Leakage

The captured CO_2 from this system is dried and pressurized to a supercritical state before being placed into a pipeline for transport to the saline sequestration site. CO_2 becomes more dense when in its supercritical phase, making transport easier and more economical (Gale and Davison, 2004). Once in the pipeline, if can be assumed that some leakage might occur, but because CO_2 pipelines are a relatively new infrastructure, little data is available on leak rates. Personal email communication with Faith Moore, a Regulatory Specialist for Denbury Onshore, LCC, stated, "Pipelines are monitored very closely by PHMSA under CFR 195 and leaks are not tolerated, other than if there is a pipe failure or a rupture of that nature" (Moore, 2009). In an effort to account for any monitoring limitations, we assumed a conservative leak rate estimate of 0.5 percent per 100 miles. This is noted as a data limitation.

This study includes little in the way of operations of the saline sequestration site. No energy or emissions associated with the day-to-day operation of the site are modeled, but a leak rate is assumed for the loss of CO_2 over the lifetime of the system. Again, this is not an established infrastructure and little is known about sequestration potential over an extended period of time. Therefore, the arbitrary value of one percent is applied as a leak rate parameter for the sequestration site. NETL believes that a saline site which may leak more than one percent would not be a candidate for CO_2 sequestration in the first place.

Water Withdrawal and Emissions

System requirements for water input to the IGCC plant with CCS are given by Case 2, Exhibit 3-38 of the Baseline Report as shown in **Table A-23**. This information sets a total water input rate 22.0 m^3/min, or 2.613 m^3/MWh of electricity delivered. Because the Baseline Report also states a 1:1 ratio of water input from municipal and groundwater supplies, the total input water to the plant from each of the two sources is calculated to be 11 m^3/min and 1.306 m^3/MWh.

The increase in water withdrawal for the case with CCS (compared to 1.857 m^3/MWh net output for the without CCS case) is due to additional water needs during the carbon capture process to cool both the flue gas before it enters the amine absorber and the column during absorption (the reaction between CO_2 and the amine solvent is exothermic) (Reddy, Johnson *et al.*, 2008).

Table A-23: Water Withdrawal for Case 2 from the Baseline Report

Water Withdrawal	Water Demand m^3/min (gpm)	Internal Recycle m^3/min (gpm)	Raw Water Makeup m^3/min (gpm)
Slurry	1.51 (400)	1.51 (400)	0
Slag Handling	0.53 (139)	0.53 (139)	0
Quench /Scrubber	2.9 (757)	0.72 (191)	2.1 (566)
Boiler Feed Water (BFW) Makeup	0.21 (56)	0	0.21 (56)
Cooling Tower Makeup	18.0 (4,750)	0.49 (129)	17.5 (4,622)
Total	25.3 (6,673)	3.25 (858)	22.0 (5,815)

Within these systems the Baseline report does not differentiate between water use (wastewater discharged to sewer) and consumption (evaporated water).

Therefore a second NETL study was used to determine the fractions of water discharged and consumed by the system (NETL, 2007b). The NETL study included an assessment of an IGCC plant consisting of two CTGs and a single STG, sized to 630 MWe of capacity, and located in Greenfield, Illinois (NETL, 2007b). The plant withdrew 404,754 lbs/h of coal. The overall water balance incorporated from the NETL study into the current IGCC plant is shown in **Table A-24**.

The NETL water loss study does not consider a plant with CCS, so some assumptions were made to account for the additional water usage. (The water discharge rate was estimated from a study with no CCS which was extrapolated to the CCS case and is noted as a data limitation.)

Table A-24: IGCC Overall Water Balance

Water In/Location	Flow (gpm)	Water Out/Location	Flow (gpm)
Moisture in Coal	48.5	Water Lost in Gasification Shift	158
Syngas Combustion of H_2 in GT	493.1	Ash Handling Blowdown	81.1
Combustion Air for GT	77.5	Water with Slag	32
Raw Water	3,824	Water Loss in COS Hydrolysis	0.5
Moisture in Air to ASU	21	GT Flue Gas	912.6
		Water Treatment Effluent	22.2
		Cooling Tower Blowdown	808.8
		Cooling Tower Evaporation	2428
		Moisture in ASU Vent	21
TOTAL Water In	4,464	TOTAL Water Out	4,464

Table A-25 sums the water loss attributed to each system within the IGCC power plant. Of these losses, all except water treatment effluent and cooling tower blowdown are consumed through evaporation. Evaporative losses were calculated to be 81 percent of the total water input. Translating this consumption rate to the Baseline Report water input, 1.52 m^3 of water is consumed per MWh of electricity delivered. Water treatment effluent and cooling tower blowdown are discharged in liquid form and total 19 percent of the water input. Translating this discharge rate to the Baseline report water input yields a total wastewater discharge rate of 0.349 m^3/MWh.

Table A-25: IGCC Water Loss by Function

Function	gpm	Gal/MWh Electricity
Gasification Losses		
Water Lost in Gasification Shift	158	18.2
Ash Handling Blowdown	81.1	9.3
Water with Slag	32	3.7
Water loss in COS Hydrolysis	0.5	0.1
Water Treatment Effluent	22.2	2.5
Flue gas loss		
GT Flue Gas	912.6	104.8
Cooling Water Losses		
Cooling Tower Blowdown	808.8	92.9
Cooling Tower Evaporation	2,428	278.9
Grand Total	4,443	510

It is important to note that the cooling water demand in the Baseline Report is based on an IGCC power plant located in the Midwestern United States; the IGCC plant in this study is assumed to be in Mississippi. The differences in elevation and ambient conditions between the two locations would result in differences in cooling water needs. This is noted as a data limitation in this study as no changes were made to the Baseline Report water data to account for the difference in location. **Figure A-18** shows the GaBi process plan for IGCC plant operation with CCS. **Table A-26** gives the GaBi air emission outputs for this process.

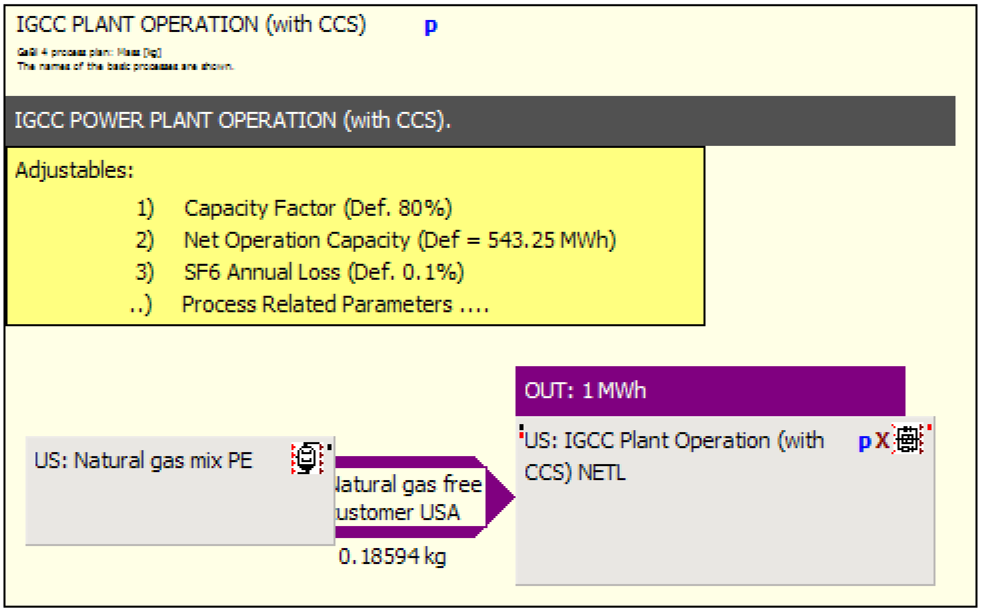

Figure A-18: GaBi Plan for IGCC Plant Operation with CCS

Table A-26: GaBi Air Emission Outputs and Natural Gas Profile for IGCC Plant Operation with CCS, kg/MWh Plant Output

Emissions (kg/MWh plant output)	Total	IGCC Plant Operation (with CCS)	US: Natural gas mix PE
Lead (+II)	1.60E-05	1.60E-05	6.29E-09
Mercury (+II)	2.90E-06	2.90E-06	5.92E-10
Ammonia	2.73E-07	0.00E+00	2.73E-07
Carbon dioxide	1.19E+02	1.18E+02	8.52E-02
Carbon monoxide	5.48E-04	4.30E-04	1.18E-04
Nitrogen oxides	2.67E-01	2.67E-01	2.56E-04
Nitrous oxide (laughing gas)	4.94E-06	3.27E-06	1.67E-06
Sulphur dioxide	1.19E-02	1.16E-02	3.54E-04
Sulphur hexafluoride	3.80E-07	3.80E-07	7.19E-13
Methane	1.02E-03	1.18E-05	1.01E-03
Methane (biotic)	0.00E+00	0.00E+00	0.00E+00
VOC (unspecified)	2.88E-05	2.81E-05	6.67E-07
Particulate Matter, unspecified	3.87E-02	3.87E-02	0.00E+00
Particles to air	7.32E-06	0.00E+00	7.32E-06

A.1.5 Life Cycle Stage #4: Product Transportation – Electrical Grid

Once the electricity is produced and sent through the switchyard and trunkline system it is ready for transmission, via the grid, to the user. A seven percent loss in electricity during transmissions was assumed for all the NETL Power LCA studies (Bergerson, 2005; EIA, 2007). This loss only impacts the cost parameters as no environmental inventories are associated with transmission lose. **Table A-27** shows how this loss is captured in the GaBi modeling framework. The transmission line was considered existing infrastructure, therefore the construction of the line, along with the associated costs, emissions and land use changes was not included within the system boundaries for this study.

Table A-27: Stage #4 Transmission Loss

Parameter	Formula	Value	Comments
Elec_loss		7%	Transmission line loss (EIA 2005)
Pow_loss	100/(100-Elec_loss)	1.0753	[%] Electricity input to the transmission line.

SF_6 leakage rate from the U.S. transmission and distribution grid are estimated using information collected and compiled from the US EPA's "SF_6 Emission Reduction Partnership for Electric Power Systems" (EPA, 2007b). Data is collected and compiled from various members of the partnership, which in 2006, represented 42 percent of the U.S. grid in terms of U.S. transmission mileage.

EPA utilizes the aforementioned data to develop the "Inventory of US Greenhouse Gas Emissions and Sinks" (EPA, 2008e). In preparing the national SF_6 leakage estimate, EPA assumes that "partners commit to reducing SF_6 emissions through technically and economically feasible means. However, non-partners were assumed not to have implemented any changes that would have reduced emissions over time."

It was noted that in 2007 and 2008, the partnership continued to grow but there was no quantification of the percent representation of the U.S. power grid. Therefore, it has been assumed that in 2007, the partnership represented 42 percent of the U.S. grid (conservative estimate which will result in slightly higher SF_6 emissions estimate). For this analysis, it is assumed that the SF_6 leak rate for non-partners (remaining 58 percent of the U.S. grid transmission mileage) will be twice that of non-partners. This value could be entered as a parameter and could be varied in a sensitivity analysis. Note that SF_6 emissions calculated in this manner exceed EPA's estimates by 5 percent (EPA, 2008e).

A.1.6 Life Cycle Stage #5: End User – Electricity Consumption

Finally, the electricity is delivered to the end user in LC Stage #5. All NETL power generation LCA studies assume electricity is used by a non-specific, 100 percent efficient process. This assumption avoids the need to define a unique user profile, and allows all power generation studies to be compared on equal footing. Therefore, no environmental inventories were collected for Stage #5.

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